The Confluence

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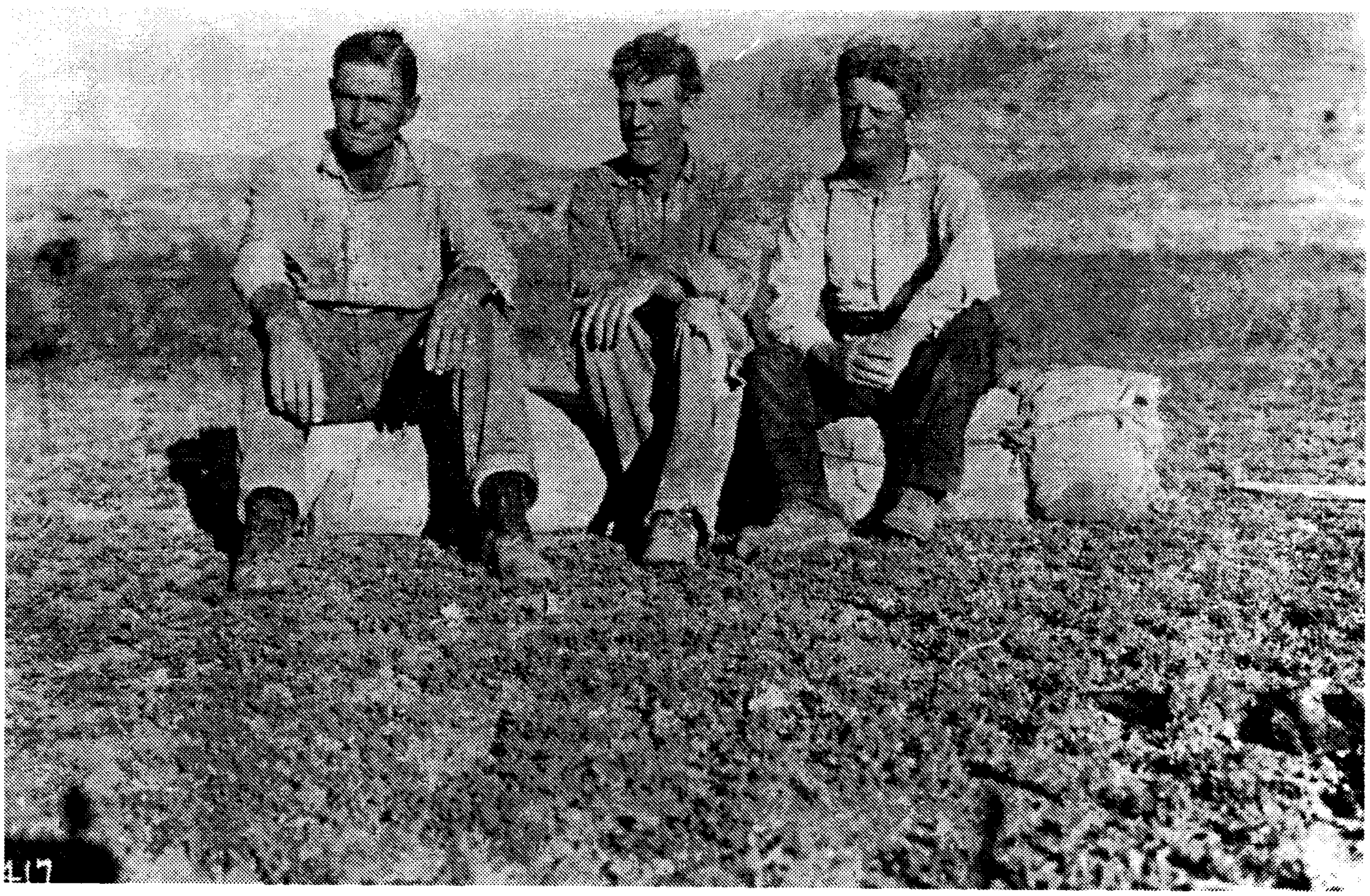


Tom Wimmer, Bert Loper and John Richardson at Loper's hermitage in Red Canyon. Glen Canyon below Hite, 1915. Photo by Eugene C. LaRue, LaRue Collection #1262. Courtesy of the United States Geological Survey Photo Library, Denver Federal Center.

Glen Canyon Dam Is Broken

by John Weisheit

The river left spillway at Glen Canyon Dam failed on June 22nd in the flood year of 1983. Several cavitation holes were excavated in the spillway tunnel, the largest being 30 feet deep and 150 feet long. In an emergency effort to save the dam they, the Bureau of Reclamation (BuRec), purchased 3/4 inch thick sheets of plywood from a Page, Arizona, lumber yard and proceeded to stack them on top of the spillways much like a building contractor would to prepare basement walls for a concrete pour. On June 29th the peak discharge, measured at the Lees Ferry gauge, was 92,600 cfs. By July 4th they had installed more dependable steel flashboards on top of the spillways. With the generators cranking, the bypass tubes blasting, and even with a damaged spillway dumping, the lake elevation finally stabilized at 3708.4 feet above sea level (asl) on July 14th, with the discharge at the Lee's Ferry gauge reading 55,200 cfs. The normal high pool elevation is 3700 ft asl.

I believe that it is possible to have Glen Canyon Dam removed in our lifetime. If the membership of Grand Canyon River Guides and Colorado Plateau River Guides persisted on this issue, we could effect the legislation needed to begin its demolition and start a process of developing alternative energy resources.

This is what Russell Martin said about the spillway failure in his book, A Story That Stands Like a Dam:

"...Bureau officials conferred and finally decided to open the east [left] *spillway gate slowly and to begin bypassing large quantities of water around the dam, the first time either spillway had been pressed into flood-control service. For more than a week, water poured into the 41-foot-diameter tunnel, its volume steadily increased until—at 32,000 cubic feet per second—the water exiting the tunnel, pouring over the deflector bucket at the tunnel outlet and spewing into the riverbed, began to turn orange, began to spit out sandstone grit, pebbles, whole boulders, even, the tunnel's concrete lining.."*

Bryan Brown and Steve Carothers, in their book The Colorado River Through Grand Canyon, reported that after the inspection of the damage, it was necessary to reopen the left spillway. **Even with parts of left spillway no longer lined in concrete, BuRec still placed trust in the left spillway; even when the right spillway still had its concrete tunnel intact.**

This is what Tom Wolf said in an article that appeared in High Country News on December 12, 1983:

"June 7. The team brings the power plant flows up to 38,000 cfs, 20 percent over normal capacity. They hold the river outlet works to 15,000 cfs (the couplings on those steel tubes were leaking). That keeps water speed down to only 50 miles per hour. And they hold the right spillway to 4,000 cfs. They want to keep it low because it occupies a dangerous position upstream from the dam's foundation. If the right spillway tunnel broke through to bedrock, it would threaten the dam's foundation."

Twenty million dollars was the cost to repair and modify the spillways; a cost that included the installation of air slots to reduce the effects of imploding vapor bubbles. They tested the left spillway at a maximum flow of 50,000 cfs (for one hour) in August of 1984. **They did not test the right spillway.**

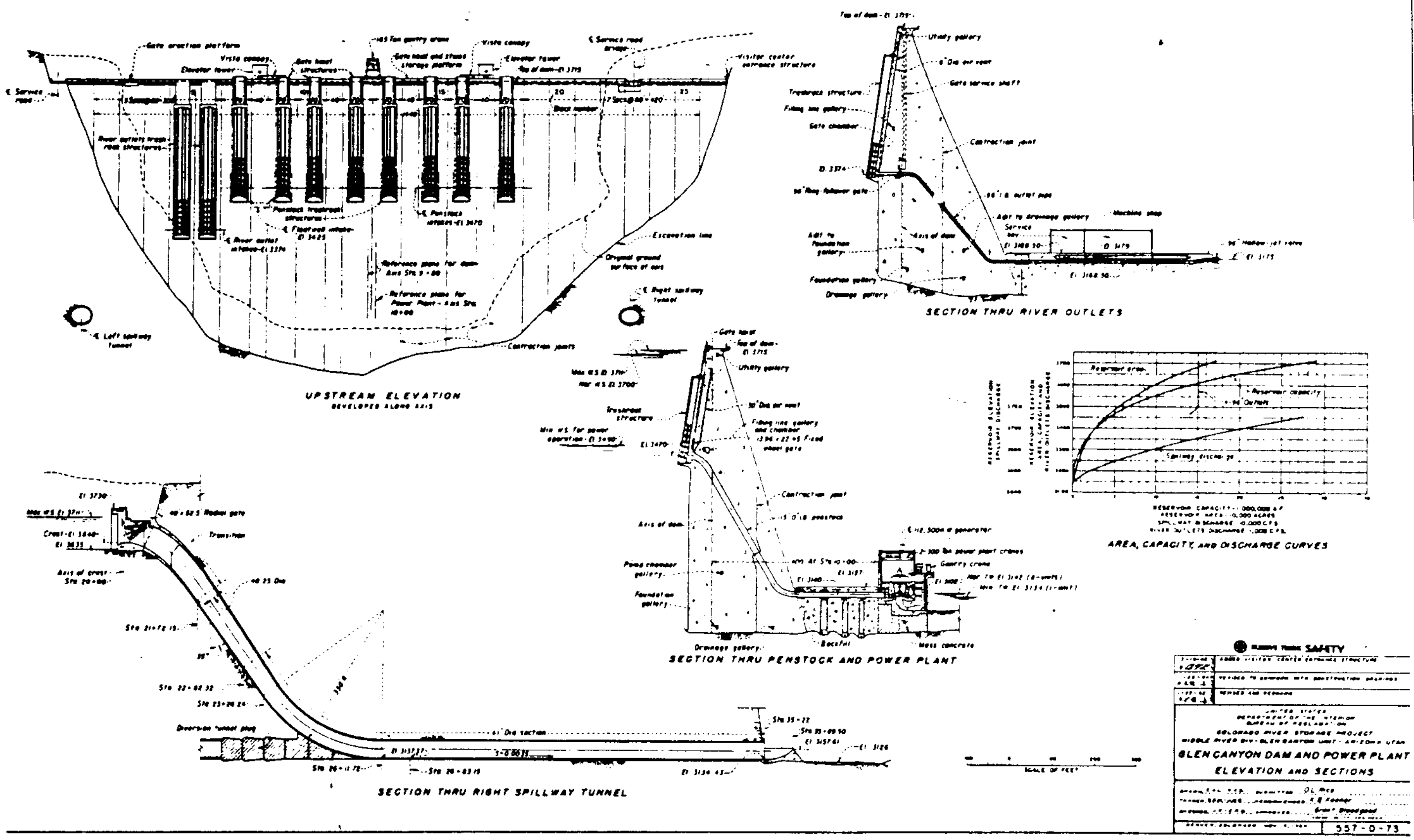
This report admits there is a structural anomaly in the shale units of the Navajo sandstone on the dam's right abutment, or keyway. I'll quote page 14:

"The Navajo Sandstone is remarkably uniform and homogenous over wide areas and nearly identical samples can be obtained from areas separated by many miles. Two thin, shaly layers, encountered at elevations 3065 and 3115 in the right abutment keyway excavation were the only changes in the lithology in the entire excavation area."

I will now quote page 24, which discusses their remedy to solve this problem:

"The seam at elevation 3115 varied from one-eighth of an inch to about 4 inches thick and had a waterflow of two to three gallons per minute. A 5- by 7- foot drift following the seam was excavated near the heel of the dam to a depth of 73 feet into the abutment to a point where the flow of water disappeared. The seam at elevation 3065 varied from a thin shale parting in the sandstone to a shale layer 1 to 2 inches thick and had a waterflow of 75 gallons per minute. A 5- by 7- foot drift following this seam was excavated near the heel of the dam to a depth of 215 feet into the abutment. The flow of water decreased with depth and at the end of the drift was just a small trickle. Both drifts were backfilled with concrete and grouted to form a barrier to seepage through the foundation."

If 3065 feet asl is the elevation at the heel of the dam, what feature is constructed at 3115 feet asl? I looked at the schematic diagrams and found a startling answer. 3115 feet asl puts you about 20 feet under the right spillway, where you will also find the concrete plugs that seal-off the original diversion tunnel. During construction this tunnel was not used to divert the normal flow of the Colorado River; being built at a higher elevation, it was used only to handle the top peak of the snowmelt.



Glen Canyon Dam and Powerplant. Elevations and sections. Courtesy of the Bureau of Reclamation.

It is reasonable to conclude that Navajo sandstone will not hold up to dynamic stress loads, such as a spillway dump; especially on the right side where there are nonconformable breaks in the rock unit. Stress loads were acknowledged as a problem in this report. I'll quote again from page 24:

"Although Navajo sandstone is remarkably uniform and yeilds remarkably smooth excavation surfaces, it has two principal characteristics which contributed to design problems. The stress-relief jointing parallel to the canyon walls showed a tendency to open slightly with time and slab or peel off onionskin fashion. The second defect is that the rock has a fairly large percentage of "set" or unrecovered strain occurring during the first loading of the sandstone. Special grouting design was developed to offset these characteristics."

There are three episodes of stress related activities for the history of Glen Canyon Dam: 1) the stress that occurred while the lake was filling when the diversion tunnels were closed in 1963, 2) when BuRec first tested the spillways in 1980, after Lake Powell finally filled, and 3) while using the right spillway in the 1983 emergency. Perhaps one or all these stresses have caused keyway damage that cannot be repaired—that is unless you drained the lake.

It is impossible to drain the lake entirely since the intake gates for the bypass tunnels are at an elevation of 3374 feet asl. Theoretically to make an effective repair of the right keyway, if such a repair could be made, you would have to reopen the original diversion tunnels. It would be like starting all over. Such a decision would seriously cripple the electrical needs of the Southwestern grid with a loss of electrical power generation from both Glen Canyon Dam and Navajo Generation Station near Page; not to mention the loss of stored water for the farmers and municipal users. **BuRec obviously has a no-action policy concerning this particular problem.**

The 1983 flood that broke Glen Canyon Dam was a twenty-five year flood that occurred early in its history. Sediment fill (aggradation) in 1983 accounted for only a 3% loss in Lake Powell's flood control potential. In 200 years Lake Powell will lose 30% of its flood control capacity due to sediment aggradation. Under these conditions the efforts that saved the dam in 1983 would have failed.

By the year 2183 Glen Canyon Dam will encounter eight 25-year floods, two 100-year floods, and one 300-year flood. Who knows when the 500-year or the 1,000-year flood is coming? One of these floods will force extended spillway use beyond the levels of 1983. The bedrock will once again fail, the diversion tunnel plugs will be hydraulically excavated, and then over 20 million acre feet of water will come racing through the Grand Canyon and into Lake Mead. If Hoover Dam were to fail, so too would Davis and Parker dams. The entire electrical grid of the lower basin would be destroyed, the aqueducts would run dry, and productive farmers would no longer grow food or cotton.

This is what I think should be done to avoid this ultimate National disaster: **1)** Congressional leaders should conduct a formal hearing with BuRec to determine the safety of Glen Canyon Dam. **2)** If the dam is considered unsafe, then it should be removed; never to be replaced. **3)** That Glen Canyon should be reclaimed and made into a national park. **4)** That alternative energy resources should be implemented into the Western Area Power Administration grid. Alternatives such as: geothermal, wind and solar resources, which are available in great abundance throughout the Great Basin desert.

In conclusion, I insist that the lifetime of Glen Canyon Dam should not be considered in hundreds of years. It is at risk today—right now! The sandstone abutments of Glen Canyon Dam are becoming structurally weaker with each passing decade and the "special grouting design's" incorporated into the construction of Glen Canyon Dam are not working.

Bibliography

Brown, Bryan T. and Steven Carothers. The Colorado River Through Grand Canyon. University of Arizona Press. Tucson. 1991.

Bureau of Reclamation. Glen Canyon Dam and Powerplant. United States Department of the Interior. 1970.

Bureau of Reclamation. Spillway Tests At Glen Canyon Dam. United States Department of the Interior. 1985.

Bureau of Reclamation. 1986 Lake Powell Survey. United States Department of the Interior. 1988.

High Country News. High Country Foundation. Ed Marston editor. Paonia, Colorado.

Martin, Russell. A Story That Stands Like A Dam. Glen Canyon and the Struggle for the Soul of the West. Henry Holt and Company. New York. 1989.

Problematic Dams in the Upper Basin

Complied by John Weisheit

From a reference book (I forgot to record the title) obtained at the Engineering Library from the University of California at Berkeley.

Fontenelle Dam
Green River; LaBarge, Wyoming.

Fontenelle Dam is an earthfill structure that was completed in 1965 and rests upon thin sedimentary beds of sandstone, siltstone and limestones, which are fractured and permeable. The dam is over a mile long, 139 feet high, and holds 345,000 acre-feet of water when full. In May 1965, as Fontenelle Dam was filling for the first time, seepage and subsequent sloughing occurred near the river left spillway. A drainage pipe was installed to remedy the seepage, but sloughing of the embankment continued. In September of 1965, during a spill, 10,500 cubic yards of the embankment eroded away. Loss of the total reservoir was avoided by high releases from outlet works. The damage was suspected to be related to the stress relief joints in the left abutment; the joints were partially filled with natural rock debris. To remedy the problem, the rock debris was injected with a concrete grout.

The dam performed normally until 1982. Spots of seepage then occurred at the toe of the dam near the left abutment and near the middle of the structure. The cause was determined to be inadequate foundation treatment during construction. The reservoir has held 10 feet below normal high pool. In 1983, the problem continued and it was decided to lower the reservoir 25 feet below high pool. In early 1985, the reservoir was restricted to 63 feet below normal pool. To remedy the problem a trench was excavated as a slurry which was later displaced by concrete injection. The concrete cut-off wall is two feet thick and runs the length of the dam to the abutments. It seems to be working for the present.

Bibliography:

"Final Safety Evaluation of Fontenelle Dam", Seedskadee Project, Wyoming, Bureau of Reclamation, Denver, Colorado, July 1984.

Bellport, B. P., Bureau of Reclamation Experience in Stabilizing Embankment of Fontenell Dam, "ICOLD", 9th Congress, Volume I, pp. 67-79, September 1967.

Navajo Dam
San Juan River; Farmington, New Mexico.

Navajo Dam is a is an earthfill structure that rests upon sedimentary bedrock of sandstones interbedded with siltstones and shales; the sandstones are moderately to highly permeable. It is 402-feet high, 3,648-feet long and the reservoir holds 1,708,600 acre-feet of water. As a result of river downcutting, joints and cracks exist in the rock parallel to the canyon walls at both abutments, but more extensively on the river left abutment. The horizontal beds of shale in the sandstone are also open (not homogenous).

Seepage at Navajo Dam was first observed on June 5, 1963 about one-year after it began to fill. When repairs were initiated (1985), seepage at both abutments was estimated to be about 1,800 gallons per minute. To remedy this problem a concrete cut-off wall was installed (as described above for the Fontenelle Dam repair). The wall is 2.7 feet wide and extends 50 to 200-feet from the left abutment and is 60 to 400-feet deep. Leakage from the right abutment was remedied by installing a tunnel and a filtered drainage system to direct seepage away from the abutments contact with the bedrock.

Bibliography:

Bureau of Reclamation
Engineering and Research Center
P.O. Box 25007
Denver, CO 80225-0007

Glen Canyon Dam
Colorado River; Page, Arizona.

Glen Canyon is an arch dam of reinforced concrete that is 710-feet tall, 1560-feet long at the crest, and holds an amazing 27,000,000 acre-feet of water. The dam's bedrock is Navajo sandstone. In 1983 rapid snowmelt and heavy rainfall in the Upper Colorado River Basin created inflows of 111,500 cubic-feet per second for the reservoir. (Please see chart.) The reservoir did not have adequate flood control potential at the time and a spill was initiated. Within three days after the left spillway began operation, portions of the tunnel's concrete lining were excavated by natural cavitation processes. To remedy the possibility of dam failure, flashboards were installed on top of the spillway gates to increase the reservoir's pool potential and thus minimize flows through the left and right spillways. The right spillway tunnel was also damaged during this incident by about half that of the left spillway. Discharges for the river right tunnel were kept as low as possible to limit damages, because the area of damage in the right spillway was further upstream than that of the left spillway (closer to the abutment).

Damage was repaired immediately by filling the cavitation holes with reinforced concrete, smoothing-out the concrete surfaces, and installing concrete slots that would introduce air into the flood flows to reduce pressures. The left spillway was tested in August of 1984. (See The Confluence, Volume 3, Issue 3, "Glen Canyon Dam is Broken".)

(continued on page 27)

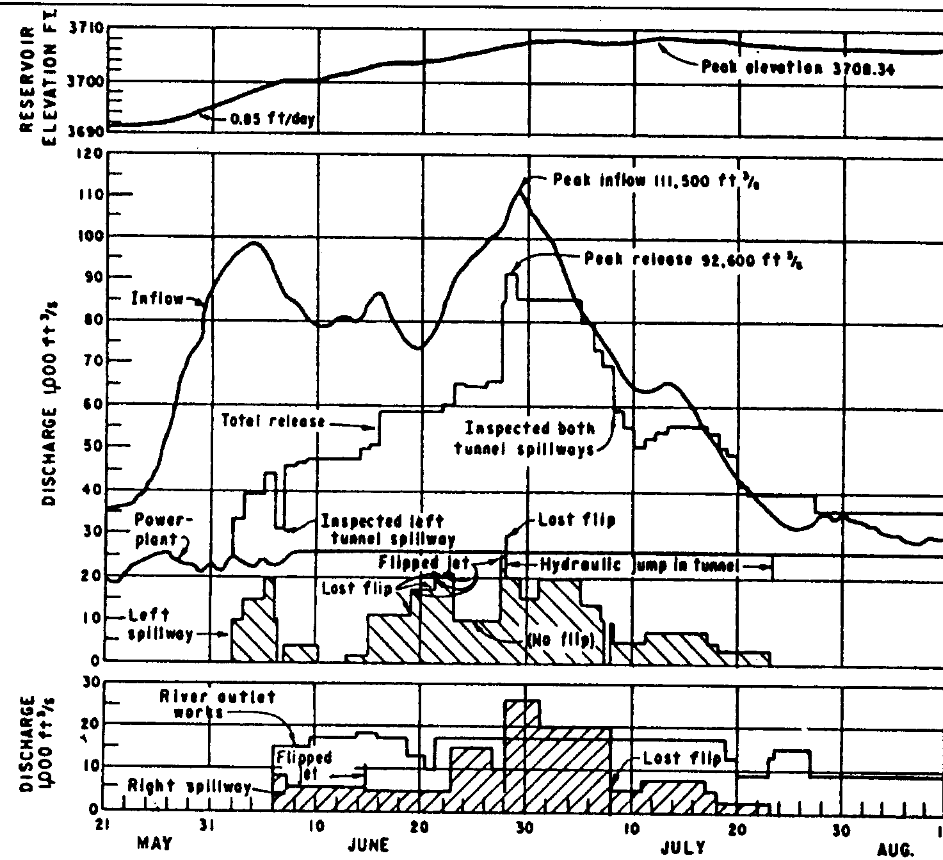
(continued from page 24)

Bibliography:

"Final Construction Report on Repair Spillway Tunnels, Glen Canyon Dam, Colorado River Storage Project", Bureau of Reclamation, Denver, Colorado, December 1984.

Burgi, P. H.: Moyes, B. M.; Gamble, T. W.; "Operation of Glen Canyon Dam Spillways - Summer 1983", Water for Resources Development, American Society of Civil Engineers, New York, NY, 1984.

Burgi, P. H.; Eckley, M. S.; "Repairs at Glen Canyon Dam", American Concrete Institute, Detroit, Michigan, March 1987.



Operation of waterways at Glen Canyon Dam, May - August, 1983.

BUMPY ROAD FOR GLEN CANYON DAM

by

W.L. Rusho

Basic Concept and Purpose

Probably no dam built in America has proved to be so controversial as Glen Canyon Dam. Built in the late 1950's and early 1960's, the dam was planned and designed to be a contributor in a long dream to subdue and conquer the earth, or as was often heard in pioneer days, "to make the desert blossom as the rose." Its basic purpose was to allow increased irrigation and other water development in the entire Upper Basin of the Colorado River, including Colorado, Utah, Wyoming, and New Mexico.

My experience with the dam is intensely personal, as I had been employed during its construction as Public Affairs Officer for the Bureau of Reclamation. For over five years during the construction I rode the monkeyslides, conducted tours for reporters and dignitaries, wrote articles and news releases, drafted speeches, conducted ceremonies, produced motion pictures, and directed the guide service and all photography. In late 1963, when the dam was virtually finished, I was transferred to the Salt Lake City BR Regional Office, which had jurisdiction over Glen Canyon Dam. From that time on I continued to be regularly involved in developments at the dam, both by many personal visits and by reports from others. Even after my retirement in 1988, I worked as a contractor producing motion pictures concerning operation of the dam and it's effect on the Grand Canyon..

Considered as a lineal descendant of the many dams constructed by the Bureau of Reclamation, Glen Canyon Dam was not unusual. Designed to be a storage dam--rather than a flood control structure--its purposes were to hold as much water as possible, release only what was necessary, and fluctuate releases as drastically as required to maximize revenues from hydropower production. After the last of eight generators came on the line in 1966, virtually the only restrictions on its operation derived from the 1922 Colorado River Compact, the 1944 Treaty with Mexico, as well as a number of related laws, all of which comprised what was loosely termed "The Law of the River."

Early History of the Glen Canyon Dam Concept

Actually, lower Glen Canyon, near where the dam was built from 1956 to 1964, had been eyed many decades earlier by hydrologists and engineers, not for a water storage dam, but for a flood control dam.

In 1906 and 1907, a tributary flood on the Salt River caused the Colorado River to break through an irrigation gate south of Yuma, Arizona and to flow unchecked for two years into the Salton Sink of California, thus forming the Salton Sea. After the gap was finally closed by dumping several rail cars loaded with rock into the breach, the river returned to its original course toward the Gulf of California. But the need for a flood control dam and reservoir was made apparent to all.

In 1921, U.S. Geological Survey engineer Eugene C. LaRue proposed, to an obsession, that Glen Canyon should be the logical site for this flood control dam. A reservoir there would hold a vast amount of water, and, even more important, it's upstream location would allow all locations downstream to be free of floods and available for irrigation development.

While the engineers were looking at possible dam sites, politicians, water managers, and lawyers were scheduling meetings with representatives of all the States within the Colorado River Basin to divide up the obviously limited (except during rare floods), flows of the river. Agreed upon and signed in 1922, the Colorado River Compact substantially divided the flows of the river between what was termed the Upper and the Lower Basins of the river, to be measured at Lee's Ferry, Arizona. Furthermore, as a concession, the Upper Basin agreed to guarantee 75 million acre feet delivery to the Lower Basin in any 10 year period, amounting to an average flow of 7.5 m.a.f. annually.

E.C. LaRue was frustrated in his campaign to have Glen Canyon made the site of the flood control dam. During the 1920's, the focus for a flood control dam shifted instead, first to Boulder Canyon, and then to Black Canyon, both within a few dozen miles of the then small town of Las Vegas, Nevada. A dam at Black Canyon would be much closer to the major hydropower markets of southern California. It would require less concrete for its V-shaped canyon, compared to Glen Canyon's U-shape. Also, a dam in Glen Canyon would be in the Upper Basin, which might be administratively difficult for Lower Basin officials to handle. The Boulder Canyon Project Act was passed in 1928, authorizing the construction of what we now know as Hoover Dam.

Although the Bureau of Reclamation had officially reserved Glen Canyon as a possible dam and reservoir site soon after World War I, construction of Hoover Dam in the early 1930's seemed to obviate the need for another main stem dam. In 1936, therefore, the National Park Service, encouraged by Interior Secretary Harold Ickes, proposed an Escalante National Monument, to cover 6,968 square miles of southeastern Utah—twice the size of Yellowstone National Park. [1] The proposed monument would have included all of Glen Canyon as well as considerable public land used for grazing.

In 1938 combined opposition from ranchers forced the Park Service to reduce the size of the proposed monument to 2,450 square miles, eliminating most of the grazing areas, but leaving Glen Canyon. Then the State of Utah weighed in—undoubtedly with Bureau of Reclamation's covert urging--favoring continued reservation of Glen Canyon as a possible reservoir site rather than a monument. Stalemated, the Escalante National Monument proposal slowly died of inaction as the Nation turned its attention to World War II.

For many years after the 1922 Compact was signed, water use in the Upper Basin was so small that there was no problem delivering the average of 7.5 million acre feet yearly that was required to be delivered to the Lower Basin. In 1944, when the United States agreed, by treaty, to deliver 1.5 m.a.f. of Colorado River water annually to Mexico, plenty of water still flowed by Lee's Ferry for that purpose. But water demands were continually growing, not only in the rapidly expanding economy of California, but also in the Upper Basin, where farmers and water managers envisioned a number of possible projects that would consume available water.

The Colorado River Storage Project Plan

[1] Farmer, Jared, *Glen Canyon Dammed—Inventing Lake Powell & the Canyon Country*, University of Arizona Press, Tucson, (1999)

Soon after World War II, Bureau of Reclamation officials printed a report entitled *The Colorado River--A Natural Menace Becomes a National Resource,*[2] in which a large number of potential projects were outlined for both the Upper and Lower Basins. Key to enabling several water projects in the Upper Basin was to be large storage capacity reservoirs that would help meet the Compact commitments to the Lower Basin. For this role, a large dam at Glen Canyon would be vitally important, as its potentially huge pool of water would insure that, in case of a severe drought, such as occurred in 1933 and 1934, irrigation and municipal projects upstream would not be denied their regular allotment of water. Other, much smaller, storage reservoirs were also envisioned on tributary rivers upstream from Glen Canyon Dam. In 1946, however, this "wish list" of projects was not yet a plan.

Eight years later, the Bureau of Reclamation published a report, actually a proposal for legislation, for what was to be termed the Colorado River Storage Project.[3] Essentially, this was a refinement of the 1946 list of potential projects, all integrated into a comprehensive plan incorporating storage dams and reservoirs to meet downstream commitments and to produce hydroelectric power. "Participating Projects" that would then be built to develop water for irrigation and for municipal and industrial uses., Revenue from the sale of hydropower would fully repay the costs of the storage projects and, although it was not called a subsidy, the revenue would also materially assist the repayment of Participating Project costs. Altogether, it appeared to be a neat package--except for one particular feature--the proposed Echo Park Unit.

Congressional Authorization

Along with the Glen Canyon "Unit" (dam, reservoir, and powerplant), the Echo Park Unit was designed as a storage unit. Compared to Glen Canyon's potential storage of 26 million acre feet of water, Echo Park would hold only about one-fourth as much., but Echo Park received the major portion of attention during Congressional hearings for one reason--the dam and reservoir were to be located in Dinosaur National Monument, in the National Park System.

Leading the campaign against Echo Park Dam was David Brower, Executive Director of the Sierra Club. By his ability to locate arithmetic errors in the Bureau of Reclamation's estimate of reservoir evaporation and through his public interviews, speeches, writings, and advertisements, the dam fell into disfavor with Congressmen, and it was eliminated from the CRSP bill. In his campaign, however, Brower linked Echo Park Dam with Glen Canyon Dam, stating that Echo Park Dam would not be necessary if the height of Glen Canyon Dam was raised to allow more water storage. In the early 1950's, therefore, Brower had no objection to construction of Glen Canyon Dam.

Many years later, during 1999 and until his death in 2000, Brower maintained that if, in the 1950's, he had known how beautiful Glen Canyon was, he could have eliminated

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[2] *The Colorado River--A Natural Menace Becomes a National Resource,* U.S. Department of the Interior, Bureau of Reclamation, GPO, March 1946

[3] *Letter from Assistant Secretary of the Interior transmitting A Report on the Colorado River Storage Project,* 83rd Congress, 2d Session, House Document No. 364, April 6, 1954

Glen Canyon Dam from the CRSP proposal by using the Congressional backing that he then possessed. Considering the political power in Congress then available to Upper Basin interests, figures such as Congressman Wayne Aspinall of Colorado and Senator Arthur Watkins of Utah, it is doubtful that Brower was correct in his half-century later second-guessing. Even Lower Basin legislators, such as Representative Stewart Udall and Senator Barry Goldwater, both of Arizona, supported the CRSP.[4]

Brower's verbal association of proposed dams in Echo Park and Glen Canyon has led many newspaper reporters, writers, and other casual observers to conclude that a dam in the latter was a substitute for the former. Actually, nothing could be further from the truth. The Bureau of Reclamation had estimated that something over 30 million acre feet of storage would be necessary to meet downstream needs should a drought such as 1933-34 recur. Since a reservoir at Echo Park would have held only 6.4 m.a.f. compared to Glen Canyon's 26 m.a.f., obviously, a dam in Glen Canyon was the key to the feasibility of the entire CRSP plan. Had Brower actually tried to and succeeded in eliminating Glen Canyon Dam, the entire CRSP would have been killed.

Furthermore, Brower's late-in-life contention that the defeat of Echo Park Dam forced the Bureau of Reclamation to raise the height of Glen Canyon Dam is incorrect; the 1954 Bureau design shows the dam crest at elevation 3,711 feet above sea level--the level of the dam as it was actually built.

This is not to say that there was no opposition to the building of Glen Canyon Dam. Contrary to the later contention of Brower and the Sierra Club, Glen Canyon was not the "place no one knew." While it was not nationally famous, it had been visited often, particularly in the 1950's, by Utah Boy Scout groups and others who simply enjoyed boating down the calm, scenic river. According to the late historian, C. Gregory Crampton, Glen Canyon was the most accessible, and therefore the most visited, of all the canyons of the Colorado River.[5] Although most people who had boated through the canyon were opposed to the dam, they were generally unorganized and no match for the steam roller of proponents pushing for water development.

Construction of the Dam

Many observers, both within and outside Bureau of Reclamation, have marveled at the speed with which construction began on the CRSP. At the time there was no need for any detailed economic or environmental studies. Following the authorization of the CRSP (Public Law 485--84th Congress) on April 11, 1956, engineers and surveyors were rushed to the site by July, and on October 15 of that year, the first ceremonial blast was set off on the canyon wall.

During 1956 and on into 1957, design engineers in the Denver Office were still hard at work producing specifications for the dam. One might wonder then why the bureau was already doing site work when the design for the dam was not yet finished. The answer is two-fold. Some work on site could be done, such as road building and planning the city of Page. Perhaps the main reason for the haste, however, was a desire to follow a well-known, time honored--and usually successful--construction strategy, which states that

[4] In later years, both Udall and Goldwater expressed regret for supporting Glen Canyon Dam.
[5] Personal interview, April 1974

when an agency starts a job that depends on appropriations from a legislative body, funding is much more assured if it seeks to *continue*, rather than *start*, a project.

According to Glen Canyon Project Construction Engineer Lemuel F. Wylie, the principal dilemma confronting him in 1956 had nothing to do with the dam, but rather with the questionable location for the construction town, later to be named Page. Since the dam site was in a remote area, in a yet unbridged canyon, completely in Arizona, but quite near the Utah-Arizona state line, political interests of both states considered it desirable to have the town established on their side of the canyon, since economic and transportation ties would probably develop early with adjoining cities. Delegations from both states repeatedly visited Wylie at his temporary Kanab, Utah office, all requesting favorable consideration.

Years later, in 1969, former Senator Carl Hayden of Arizona publicly stated that Page had been so located because of his request to place it on the Arizona side.[6] Considering that in 1956 Hayden was Chairman of the Senate Appropriations Committee, it was a foregone conclusion that the bureau would agree. A large spring of good water had been located on the Utah side, leading some engineers to recommend that location,[7] and a perfunctory examination was made there. But considering Senator Hayden's expressed preference, the only real question was precisely where on the sandy Arizona side the town would be placed. Wylie reported in an interview that he and Louie Puls, Chief of the Concrete Dams Section of the Chief Engineer's Office, hiked along the sandy Arizona side in July 1956, found nothing suitable, then decided to examine a low plateau about a mile to the east. After hiking to the top, the two looked around, then Puls said, "Lem. What's the matter with this?" Wylie replied, "Not a thing--not a thing."[8]

So the town of Page was situated on the Arizona side, on Manson Mesa. But the selected town site had another difficulty--it was located on the Navajo Indian Reservation. To resolve this Wylie and Department of the Interior lawyers met with tribal officials several times without conclusion, until one of the lawyers suggested a land trade. This idea met with favorable response, resulting in the Government's obtaining 55,000 acres of land for Page and for the Navajo side of the future reservoir in exchange for a like amount of land on McCracken Mesa in southeast Utah.[9]

When asked about problems encountered while building the dam, Wylie could think of nothing major. "It was mostly mechanical," he said. "The contractor knew what to do, I knew how to handle day to day problems, and I had a competent staff to insure quality construction."

A labor strike shut down construction of the dam for six months, from July to December, 1959. The dispute arose when the prime contractor, Merritt-Chapman and Scott, curtailed making extra housing payments, up till then paid to employees for the remote location of the job, after determining that housing was available in Page and in company dormitories. The strike was finally settled near Christmas 1959, and by January 1960, the work was again well underway. No event delayed construction from that point on, and the dam and powerplant were finished on schedule.

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[6] Remarks by Carl Hayden at the Carl Hayden Visitor Center, October 1969

[7] Interview with Clyde Gessel, March 1999.

[8] Interview with L.F. Wylie, June 1983

[9] Ibid.

Archaeology and History Investigations

Today, with the National Environmental Policy Act of 1969 in effect, no project can be undertaken on federally-owned land without a preliminary and thorough archaeological and historical investigations (as well as many other studies), of the area to be impacted. In 1956, however, no NEPA rules were in effect, so Glen Canyon received no studies prior to inundation that would be considered as counter to authorization of the dam. What it did receive was what was called simply the Glen Canyon Archaeological Salvage Project. In compliance with the Historic Sites Act of 1935, the National Park Service obtained funding and let two contracts for the work. The largest was awarded to the University of Utah to investigate the right bank of the Colorado, the triangular area between the Colorado and the San Juan, and the left bank of the Colorado above the confluence with the San Juan. The Museum of Northern Arizona was authorized to examine the south side of the Colorado and the San Juan.

Even before 1956, Glen Canyon and the San Juan River Canyon were known to have substantial numbers of archaeologically significant sites, including dwelling areas, granaries, trails, petroglyphs and pictographs. Several private or institution-sponsored research expeditions had ventured into the region, particularly in the 1930's. Prominent among these was the Rainbow Bridge—Monument Valley Expedition, (RBMVE), a cooperative effort by the National Park Service and several universities, which operated from 1933 to 1938.[10] Although the RBMVE only touched on Glen and the San Juan River Canyons, its crews found numerous archaeological sites, although few were excavated at that time.

Initiating the Salvage Project in 1957, with the dam already under construction, both the University of Utah and the Museum of Northern Arizona sent qualified crews, consisting of archaeologists, helpers, students, horse wranglers, boatmen, and cooks, into the canyons and onto the surrounding areas. To obtain base data for regional comparison, they also surveyed archaeological sites on highland areas, such as the Kaiparowits Plateau and Cummings Mesa.

Dr. Jesse D. Jennings, director of the University of Utah effort, devised special techniques to help speed the project. For instance, he enjoined crew chiefs to "use the coarsest tool that will do the work—i.e., recover the data. A shovel can be as useful as a trowel, a road patrol or scraper as useful as a shovel, or a dragline as useful as a pick, in the hands of an excavator who is free of ritual compulsiveness."[11] Of course, there was no way to get a road patrol, scraper or dragline into the canyons, but his philosophical approach had the merit of accomplishing as much as possible in the time available.

Every means of transportation was tried as a means to get crews into the main and side canyons, from airplanes, to four wheel drive vehicles, to horses and mules. But the areas were so rugged and remote that the rivers themselves became the main travel and

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[10] Christenson, Andrew L., *The Last of the Great Expeditions—The Rainbow Bridge/Monument Valley Expedition, 1933-1938,* Plateau Magazine, Vol. 58, No. 4, Museum of Northern Arizona, Flagstaff, AZ, (1987)

[11] Jennings, Jesse D., *Glen Canyon: A Summary,* University of Utah Anthropological Papers, No. 81, Salt Lake City, (June 1966), p. 7

communication lines. Small, outboard powered aluminum boats were extensively used, with occasional recourse to rubber rafts.

According to Jennings, the Survey found and recorded over 2,000 archaeological sites, of which about 80 or 85 were fully or partially excavated.[12] In confirmation, Don Fowler, one of Jennings' crew chiefs during the 1957-1963 survey, estimated that due to lack of time, less than 10 percent of the sites were examined in any detail. But both Jennings and Fowler agreed that the survey was adequate to determine the population densities at various stages of pre-historic cultures. Dispelling earlier rumor, no large ruin, such as at Mesa Verde or Chaco Canyon, was found.

Writing as a professional archaeologist, Jennings could not praise the Glen Canyon Salvage Project highly enough, for it finally provided adequate funding for substantive research, as opposed to piddling, poorly funded studies in previous years. He wrote that over 30 previous explorations of Glen Canyon by problem oriented or pot hunting men resulted in no scientific account.[13]

> *I suggest that in virtually any detail, and certainly in overall results, emergency salvage archaeology is superior to most other work done in America.*[14]

Jennings, now deceased, therefore did not lament the drowning of 2,000 archaeological sites. He proudly pointed to the many volumes of useful and accurate scientific data that were recorded in monographs and books. And besides the data, he and his researchers had accumulated a museum full of small artifacts available to future archaeologists.

On the personal side, Jennings wrote that

> *. . . learning the Glen and working in and near it for six or seven summers was a rich, emotionally charged period of my life. The vastness, the isolation, the stillness, the overwhelming beauty of the land, even (especially) the heat, the still starlit nights, the blue or brassy midday sky, all combined to make me constantly aware of my good fortune. . . . millions of vacationers each year fish, swim, water ski, wind surf, and camp in the tributaries and some spots on the lake itself see and enjoy much of the same natural beauty as I once did. But the intimacy of the river and the side streams is gone, and all my hard won knowledge of the sandbars, the shoals, and the camping sites is now obsolete, but remain bright in memory.*[15]

In the original Glen Canyon Salvage Project, no separate provision had been made for historical research, as it was assumed that archaeologists could record any rare historic site while in the course of their regular tasks.

Dr. C. Gregory Crampton, historian at the University of Utah took it upon himself to address the lack of historical research as a dedicated project by writing to the National Park Service and convincing them of the omission. Consequently, Crampton himself was

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[12] Jennings, Jesse D. *Accidental Archaeologist—Memoirs of Jesse D. Jennings*, University of Utah Press, Salt Lake City, (1994). P. 215

[13] Jennings,; *Glen Canyon: A Summary*.

[14] Ibid.

[15] Jennings, *Accidental Archaeologist*, p. 216-217

given $25,000, expected to be enough to do the job. With such limited funds, Crampton could hire no one, but had to do all the research himself, using only unpaid graduate students (loosely termed "slaves"), as assistants.

During the years 1957 to 1963, Crampton tediously filed through old mining records, courthouse documents, diaries and manuscripts, and newspaper accounts. Following written leads, he then made eight float trips, each with one or two graduate students, to stop at specific sites mentioned in the written records. With his funds nearly exhausted, Crampton, with my urging, persuaded Frank Clinton, Regional Director of the Bureau of Reclamation, to authorize and fund boat trips down the San Juan River in 1962 and down Cataract Canyon in 1963. On these last two trips, I traveled along, acting as official photographer, as we stopped and recorded numerous historic sites.

From 1959 to 1963, Crampton wrote seven detailed monographs, complete with maps, photographs and documentation, each published as an Anthropological Paper by the University of Utah. Following these works, he published *Standing Up Country—The Canyonlands of Utah and Arizona,*[16] in which brought Glen, Cataract, and San Juan Canyon histories into a regional perspective. He followed this with *Ghosts of Glen Canyon,*[17] a series of Glen Canyon historical vignettes and photographs arranged by river mile. In these books he repeatedly emphasized the point that Glen Canyon, containing hundreds of historic sites, was the most historic of all the canyons of the Colorado.

The Rainbow Bridge Problem

In Public Law 485 authorizing the Colorado River Storage Project are the words:

> *That as part of the Glen Canyon Unit, the Secretary of the Interior shall take adequate protective measures to preclude impairment of the Rainbow Bridge National Monument.*

These foregoing words were inserted at the insistence of environment groups, including the Sierra Club, the Wilderness Society, and the National Parks Association, with the intention of preserving Rainbow Bridge and its surrounding160-acre enclave set aside as a national monument in1909, in its natural state.

Congress also included the following clause:

> *It is the intention of Congress that no dam or reservoir constructed under the authorization of this Act shall be within any national park or monument.*

This clause was inserted as an affirmation of Congressional opposition to a dam in Dinosaur National Monument (Echo Park), as well as a desire to keep Glen Canyon reservoir water out of Rainbow Bridge National Monument.

In regard to Rainbow Bridge, the Bureau of Reclamation faced a delicate situation, namely, how to keep reservoir water out of the monument without tearing up the

[16] Crampton, C. Gregory, *Standing Up Country—The Canyonlands of Utah and Arizona,* Alfred A. Knopf, New York; University of Utah Press, Salt Lake City, in association with the Amon Carter Museum of Western Art, Fort Worth.

[17] Crampton, C. Gregory, *Ghosts of Glen Canyon,* Tower Productions, Salt Lake City (1986 and 1994)

surrounding landscape, and how to build a barrier dam quickly enough so that the reservoir could be allowed to fill without an untimely delay.

By the terms of P.L. 485, the bureau had no choice but to keep water from the future Glen Canyon reservoir from entering the boundary of the Rainbow Bridge National Monument. Created by Executive Proclamation in 1909, the 160-acre monument lay about 5.5 winding stream miles southeast of the Colorado River. As the reservoir rose, it would enter the monument area at elevation 3,606 feet above mean sea level., and at its planned maximum elevation of 3,700 feet it would be 45 feet deep in the channel beneath the bridge, but still 21 feet below the lowest abutment of the bridge itself.[18] Therefore, to keep reservoir water out of the national monument, as required by law, would necessitate some kind of downstream barrier dam.

It was obvious to those of us who worked for the agency at the time that top officials of the bureau would build a barrier dam only after considerable loud protesting. And the most effective way to ward off building such a dam was to postpone specific Congressional appropriation—perhaps indefinitely. One bureau publication stated:

> *Much of the earth materials required for construction of any possible restraining dams would have to be obtained from the top of the high mesa [1,200 vertical feet above the stream channel]. Heavy equipment to work the high mesa borrow area would have to be lifted to the mesa top by cableways or carried in by helicopter, as it would be impossible to build a road on to the high mesa. . . . .the high mesa borrow operations would necessarily leave certain unavoidable and irremovable construction scars.*[19]

One might question why the bureau would resist building a barrier dam, since, after all, the agency was in the business of building dams. At least one author, Hank Hassell, in his book *Rainbow Bridge—An Illustrated History*, felt that it was simply pay back to the Sierra Club for having embarrassed the bureau in the Echo Park Congressional hearings.

> *With the benefit of hindsight it now seems clear that the motive of both Congress and the bureau was simple one-upmanship. Western states congressmen had been stung and stung badly by Dave Brower's success in stopping Echo Park Dam. The bureau, too, felt that it had been publicly humiliated on its own turf, and now both bodies saw a way to strike back.*[20]

Three possible sites were examined for a barrier dam in the deep, narrow canyons leading from Rainbow Bridge down to the Colorado River. The middle site, Site B, preferred by the bureau, would have required a small dam *upstream* from the bridge and a tunnel to divert natural runoff to an adjacent canyon.

Dam site C, further downstream, would not have required the diversion structures, but would have required a large dam, 365 feet high, with a crest length of 800 feet. It could have been constructed by building a haul road from the north, with a bridge over the

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[18] Bureau of Reclamation, limited publication document, (1959), copy in possession of the author
[19] Ibid.
[20] Hassell, Hank, *Rainbow Bridge—An Illustrated History*, Utah State University Press, (1999), p. 126

Colorado River, and much of the construction scars would have been inundated by the future reservoir, yet it was never seriously considered by the bureau. The reason was simple—it would have taken too long to build, and was at too low an elevation. The site C dam would have had to be in place before the gates at Glen Canyon Dam were closed. Such a situation would have set back the filling schedule for Lake Powell and was considered unacceptable.

The bureau, through the Interior Secretary, in 1960 dutifully asked for $3.5 million in appropriations (of the projected $25 million final price), to begin construction of the structures to protect Rainbow Bridge. But heavy lobbying by Senator Frank Moss of Utah, Congressman Wayne Aspinall of Colorado, and Floyd Dominy, Commissioner of the Bureau of Reclamation, convinced the House Appropriations Committee to delete the line item from the budget with the words, “no part of the fund herein appropriated shall be available for construction or operation of facilities to prevent waters of Lake Powell from entering any national monument.”

In 1961, Interior Secretary Stewart L. Udall, recognizing that building a dam at site B would leave disastrous construction scars on the landscape, sought a way out by proposing a new national park that would encompass, not only Rainbow Bridge, but also much of the fantastically eroded landscape—all Navajo land--in surrounding areas.. On April 9, he organized a mass visit to the bridge by environmental representatives, news reporters, and governmental officials to promote what he called Navajo Rainbow National Park, with helicopter transportation furnished by the U.S. Air Force and by private air services. Although his concept had merit—it would have been a magnificent national park—one key provision of his proposal was to put the boundary of such a park at the normal high water line of Lake Powell, thus eliminating the need for a barrier dam, and Dave Brower and others would not accept the concept. Also, Udall had failed to consult with Navajo Tribal leaders, who were miffed at the slight. The Navajos abruptly refused to give part of their land for a new National Park,thus killing the proposal.

During the 1960’s, Congress each year expressly denied funds for a barrier dam, inserting the same prohibitive clause in the Appropriations Bill. In August 1962, the National Parks Association, the Sierra Club and other conservation organizations filed suit, asking for an injunction to prevent the closing of the gates at Glen Canyon Dam until protective works for Rainbow Bridge were at least under construction. The judge, however, dismissed the suit, ruling that the organizations had no standing in law as they would not suffer harm by the filling of Lake Powell. Upon that note, the bureau closed most of the diversion tunnel gates on March 13, 1963, and Lake Powell began a rapid rise.

As lake waters crept up the narrow canyons toward Rainbow Bridge, Dave Brower, now head of a new organization called Friends of the Earth, enlisted the Wasatch Mountain Club and Ken Sleight, owner of a river running company, (the last two providing standing to sue), to join him in a suit to keep Lake Powell waters away from the bridge. In November 1970, the suit was filed, asking only that Lake Powell be limited to elevation 3,606, thus keeping it out of the national monument, in accordance with Section 3 of Public Law 485. On February 27, 1973, Judge Willis Ritter, in Salt Lake City, granted the plaintiff’s motion and ordered the bureau to lower Lake Powell to the 3,606 level. To the bureau and to Upper Basin water users, this was a disastrous decision, for the top 94 feet, from elevation 3606 to 3700, contained almost half of the storage volume of the reservoir.

Furthermore, the lowered reservoir would substantially reduce the hydraulic “head” on the turbines, thereby cutting power production and revenue.

Of course the government appealed and on May 1, 1973, a three-judge panel of the Tenth Circuit Court of Appeals voted 2 to 1 to allow Lake Powell to enter Rainbow Bridge National Monument while the case was reviewed. Then, just three months later, the Appeals Court issued its decision. Voting 5 to 2, the Court held that Congress had indeed repealed Section 3 of Public Law 485 by repeated acts of denying funds for protective works. Chief Justice David T. Lewis strongly dissented, commenting that the decision “was a deep trespass upon the prerogatives of Congress and a clear and dangerous violation of the doctrine of separation of powers. . . .[and] an equally dangerous judicial aggression.”

Brower and his lawyers appealed to the Supreme Court, where the conservation case was joined *amicus curiae* by Attorneys General of 16 states—all of which disagreed with the Appeals Court decision. Out of four required, however, only three Supreme Court justices agreed to hear the case. Therefore on January 21, 1974, the Court announced that it had denied the appeal and that it would not review the case. Thus a new legal precedent, *repeal of a law by implication,* had been set. And Lake Powell would continue to rise. And it rose, faster than almost anyone had predicted.

The Spillway Crisis, 1983-1984

Of course, the lake level fluctuated up and down in accordance with seasonal runoffs, and in some years it declined more than it rose. Generally, however, the level was higher each year until the lake actually filled, to elevation 3,700 on June 22, 1980, an event that was marked by a public celebration on the crest of the dam. As a demonstration, both spillways were slightly opened for a short time. Lem Wylie, who had supervised the construction and who was invited as a guest for the celebration, expressed amazement at the rapid filling. “I never expected to see this in my lifetime,” he stated.

Yet the filling in 1980 was only prelude to a much more dramatic event. Runoff prediction is an inexact science, but predictions are vital for reservoir regulation. Any storage reservoir, such as Lake Powell, should be kept as full as possible, with accidental spills kept to a minimum. Therefore, runoff predictions are necessary early each spring so that sufficient space—but not too much--can be provided in the reservoir.

In 1983, nature dealt predictors a bad hand. Accumulated snowfall in the mountains on April 1 was only a bit above average, but the snow kept falling—in increasing amounts. By early May it appeared that Lake Powell had insufficient space for the runoff, so the bureau opened the wicket gates of the powerplant so as to operate at full capacity, night and day. Still the water rose steadily toward the full mark of elevation 3,700 feet. The four outlet tubes, capable of a combined 11,000 cubic feet per second release were also opened.

Two spillways have been provided at Glen Canyon Dam, not through the dam itself, but through the rock wall on each side of the canyon. These sharply descending tunnels, originally lined with three feet of concrete, were sized to handle a massive 180,000 cubic feet per second, yet their expected use would be rare, with small flows of short duration.

Early in June 1983, however, with the lake still rising, one spillway radial gate (a heavy steel gate that is raised to admit flow from the bottom), had to be opened to allow water into the left spillway. When this operation is performed, water roars into the spillway, drops precipitously through several hundred feet, until it reaches the elbow section, then flows through the lower end, at that point horizontal, of what had been the diversion tunnel. Upon exiting, it strikes a "flip bucket" designed to dissipate the tremendous energy by throwing the water high into the air, allowing it to fall into the Colorado River. In 1983, the operation worked as expected—except for the insidious phenomenon known as cavitation.

All civil and mechanical engineers are familiar with cavitation, a process where a fast moving liquid is thrown upward by some small obstruction, thus creating vapor cavities, or small vacuum pockets. These cavities then collapse with destructive force, digging holes into the surface on which the liquid is flowing. The holes are rapidly enlarged and deepened. After one hole is formed a leapfrog action is initiated, causing further cavitation holes to form on down the surface. One might ask why designers specified spillway tunnels that were almost certain to suffer cavitation damage when used. The only answer is that a well-managed reservoir should almost *never* spill, and then only for very short periods, after which the cavitation could be repaired.

Although a spillway tunnel had been provided on each side of the canyon, the right, or west, spillway was not used initially so as to confine the cavitation damage to the left one. As the inflow into Lake Powell topped 100,000 c.f.s. the gates were gradually opened until 32,000 c.f.s. roared through the left tunnel. I was one of the witnesses who saw the outflow turn orange, hurling chucks of concrete and sandstone into the Colorado River. Most of the engineers were somewhat worried, although they knew that—theoretically at least--most of the damage would be downward—not laterally into the lake. Yet obviously a hasty inspection was in order.

With the gates temporarily closed, two intrepid engineers, clad in foul weather gear, rode a tugger-lowered cart into the dark left spillway. Almost 600 feet down the 60 degree slope they encountered massive holes clear through the three-foot thick concrete lining, and into the sandstone, reinforcing bars twisted and broken. Just beyond they could see a series of large holes further down. At this point they could go no further and were hoisted back to the daylight.

By the end of June, when the inflow into the lake rose to around 120,000 c.f.s. and the gates of both spillways had to be opened. The biggest worry was not that the lake would top the dam, elevation 3715, but that the water would rise above elevation 3700, at which point the water would flow over the top of the gates, even if they were in closed position. Work crews hurriedly placed temporary 4'x 8' plywood panels upright across the top of the gates so as to increase storage. To a non-engineer, it sounds fantastic to hold back a 186-mile long lake with plywood panels—but it worked.

For a more permanent and effective fix, heavy steel 8-foot high flashboards were fabricated and trucked to the dam. Even as a large flow of water was roaring under the gates, workmen on top of the gates starting installing these flashboards on July 4th, working around the clock, and within two days they were in place.

On July 14, the lake level reached 3708.4, held at that elevation for almost a day, then began a slow, but measurable, decline. The flood of 1983 was over. By early August all spillway flows were curtailed.

But the big job of spillway repair had yet to be determined. I was one of a team who, in late July, waded into cold, standing water of the left tunnel and proceeded up the dark cavern toward the elbow section. It was an eerie spelunking experience to be entering that awesome dark underground chamber, not quite sure of what we would find. Pulling a raft laden with battery powered floodlights, we scrambled and climbed around and over an amazing array of rock rubble, at least one piece as large as a good sized automobile. In many places the concrete lining was entirely gone, with rebar broken off by metal fatigue. Apprehensive of the expected large hole at the elbow section, we stopped wading short of having to swim, but from our vantage point we could easily see the series of large cavitation holes just above the elbow section. Having recorded the damage on film and videotape, we retraced our route to the sunshine.

With the powerplant operating at full tilt, and with all four outlet tubes shooting eight-foot wide jets into the Colorado River, emergency repairs began on the spillways. Drained of water, adit tunnels were gouged into the lower sides of each tunnel, near the outlet portals, to allow access to heavy equipment and trucks. A contractor hired hundreds of men and women to remove broken concrete, loose sandstone, and to prepare the tunnels for new rebar filled concrete lining. When the huge hole at the elbow section of the left tunnel—the most severely damaged—was drained, it was measured to be 32 feet deep, 40 feet wide, and 150 feet long. It took twenty-five hundred cubic yards of concrete to fill the hole.

Meanwhile in the Denver Engineering Laboratories, engineers were giving final touches to the design for air slots to be incorporated in the upper portion of the Glen Canyon spillways. Their design called for a four-foot wide, four-foot deep, circular trench to be cut and lined about 110 feet down from the upper portal of each spillway. Tests had shown that when high velocity water crossed these air slots, a cushion of air bubbles would be introduced, on which the water would ride through the remainder of the spillway. Cavitation would therefore be virtually eliminated.

The general principle of using air slots on tunnel type spillways had been conceived by design engineers during the 1970's, had been tested, and had actually been retrofitted into the spillways at Yellowtail Dam in Montana. Whenever funds permitted, air slots were planned for all Bureau of Reclamation dams with tunnel type spillways. Had the 1983 damage not occurred, the spillways at Glen Canyon Dam would probably have been retrofitted with air slots sometime during the 1980's. But with a large contractor on site, it was logical to build in the air slots as part of the ongoing spillway repair.

Also, so as to prevent surprise incidents like the 1983 runoff, it was apparent that runoff forecasting had to be improved. bureau officials in Salt Lake City, in cooperation with the National Weather Service and the Soil Conservation Service, devised an improved forecasting model, and ways to quickly refine that model as snowfall in the mountains accumulated. It was not accomplished too soon.

As work on the spillways progressed through the fall of 1983 and into the new year, large amounts of snow continued to fall in the high country, and the 1984 forecast showed that the runoff could be even greater than in 1983. With the spillways temporarily out of commission, it was obvious that releases of water through the dam and powerplant had to be kept at a maximum. Through May and June Lake Powell inched upward until it was only a few inches from the top of the new flashboards on the spillway gates. Then in early July the lake level began to recede. The crisis point had been passed.

On August 12, 1984, the left spillway, completely repaired and incorporating an air slot, was tested with a release of 50,000 c.f.s. The event was astounding to watch, as huge jets of water arced gracefully from the flip buckets over 100 feet before plunging violently into the river. Spray filled the downstream canyon, refracting rainbows from the bright summer sunlight. After a few days of testing, the flow was curtailed and the spillway pumped dry for an inspection. I was fortunate to accompany the team of engineers that went in to examine the concrete surface. We could see no damage whatsoever. The air slots had been a complete success in preventing cavitation.

Altogether, the repair of the two spillways had cost around $30 million, but the steady full operation of the powerplant to release more water had netted around $34 million in extra revenue. Furthermore, as most of the power was sold to energy companies in California, it enabled them to save great quantities of oil that would have been burned in oil-fired generating plants.

Glen Canyon Power and the Grand Canyon Ecosystem

Almost simultaneous with the spillway crisis, Glen Canyon Dam hit another bump in the road. For many years, even before the dam was completed, biologists, geologists, archaeologists and river runners had been concerned with the altered character of the Colorado River flowing from the dam and through the Grand Canyon. What enters Lake Powell as a warm, silt filled river emerges through the dam as cold and clear, similar to a mountain stream. It also fluctuated high and low in accordance with power demands at the Glen Canyon Powerplant, sometimes very rapidly. No studies had yet been made, but most scientists predicted damage to the Grand Canyon ecosystem.

What caught the attention of the public, however, was a Bureau of Reclamation proposal to increase the power producing capacity by adding generators to the outlet tubes. Since peaking power earns considerably more revenue than off-peak power, the idea had been to convert the entire powerplant into a peaking power operation. Outflows during off peak would be practically curtailed, while during peak power demand, all eight generators, increased to 12 by addition of the four on outlet tubes, would be operated at full capacity. And to maintain steady flows through the Grand Canyon, a re-regulating dam, about 30 feet high, built to contain a fluctuating reservoir, was planned for the canyon a few miles below the dam. To bureau officials intent on finding ways to increase revenue the plan was a good one, but it struck a very large obstacle—public opinion.

In 1981, during public hearings in Page, Flagstaff, and Salt Lake City, the proposal aroused the ire of many who simply did not want another dam, even a small one, built in Glen Canyon. To them, the hated concrete dam was bad enough; they were not going to let the bureau flood the last 15 miles of Glen Canyon below the dam. Fishers, in particular, who reveled in those 15 miles of good fishing, cried foul. Even river runners, who might be expected to embrace the idea of a non-fluctuating river below Lee’s Ferry, were vocal in opposition. Many of these opponents wrote newspaper articles, appeared on national television, and urged people to write protest letters to their Congressmen.

Within a few months, the bureau surrendered, giving up the proposal, but opting instead to rewind each of the eight generators at the dam so as to increase the power output, which would not change river flow patterns. The public protests, however, had called attention to possible damage the clear, cold, fluctuating river was doing to the Grand Canyon ecosystem. Responding to this pressure, Under Secretary of Interior Robert Broadbent ordered a thorough study of several scientific aspects of the riverine environment below the dam. Although it was officially called the Glen Canyon Dam Environmental Studies, (because in concerned the flow releases from the dam), all of the studies were to be made in the 15 miles remaining of Glen Canyon, and in the 275 miles of the Grand Canyon.

With the Bureau of Reclamation as prime agency, cooperation and assistance was needed and obtained from the National Park Service, the U.S. Geological Survey, the U.S. Fish and Wildlife Service, the Arizona Game and Fish Department, several universities, and many Indian tribes. Researchers from all of these agencies and institution spent over ten years investigating every possible change brought about by the flow regimen over the previous 20 years. For two years, from 1983 to 1985, they were hampered by the continual high releases, and virtually no fluctuations, required by the spillway crisis, thus creating an abnormal flow pattern. Most substantive investigations therefore began after the spillways had been repaired.

Researchers knew, even before they ventured into the Grand Canyon, that the clear water and fluctuations would be having some effect; the only question was how much. All of the sand, silt, and many of the minerals that used to flow though the canyon, nourishing the beaches and riverine life zones are now continually captured by Lake Powell. Furthermore, clear water accelerates degradation of the stream bed and shorelines, causing much of the existing sand to disappear into the river. High flows and rapid and wide fluctuations in river flow due to changes in power demand at the Glen Canyon Powerplant add substantially to the degradation.

Before 1963, the temperature of the river in Grand Canyon was synchronized with the seasons, warm enough to support a warm water fishery that included pike minnow, (formerly known as squawfish), razor backed suckers, bony tailed chub, and hump backed chub. Researchers suspected that these four species, having been impacted by cold water flows for over two decades, and all now listed as endangered, would have all vanished from the canyon.

After ten years of research, at a cost of about $100 million, almost all of the predicted results were confirmed, however huge amounts of additional data were obtained concerning the downstream ecosystem. Voluminous reports and books have been written on the findings.

Here are a few examples of what was learned. A viable humpback chub population was discovered in a relatively small estuary where the warm Little Colorado River flows into the Colorado River. But all the other endangered fish species had vanished from the canyon. Rainbow trout, however now live in the cold river, in reduced numbers as the distance from the dam increases. Surprisingly, bald eagles have begun to frequent the canyon to fish in the lower mile of Nankoweap Creek, where trout spawning occurs.

Tamarisk, *tamarix, ramosissima,* a water devouring phreatophyte, was found to have greatly spread along the river banks, largely due to the lack of high, sand-laden spring runoff flows to uproot them and wash them away. However, several bird species, such a Bells vireo, summer tanager, hooded oriole, and great-tailed grackle, have greatly expanded their nesting range throughout the dense foliage of the tamarisk and other bushes that now line parts of the river.[21]

So that left only the question of how the operation of the dam could be altered so as to minimize deleterious effects on the Grand Canyon ecosystem. In November 1989, the Secretary directed an Environmental Impact Statement (EIS) be prepared on the operation of the dam, with Reclamation again as the lead agency. Expressly ruled out was the option of removing the dam. So also was drilling a prohibitively expensive one-hundred mile tunnel to convey sediment from the upper part of Lake Powell around the dam to the canyon. As for the cold water releases from the depths of the lake, the bureau agreed to study ways to raise the temperature by modifying the intake structures.

In early 1991, the bureau changed the flow regime by raising the minimum flow, by cutting the peak off maximum flows, and by slowing down the “ramping,” speed where flows are altered either up or down. The final EIS, completed in March 1995, and the Record of Decision, (October 1996), essentially recommended perpetual maintenance of this pattern, except in emergencies.

Congress passed the Grand Canyon Protection Act of 1992, requiring some type of continual monitoring of effects on the downstream ecosystem, now complied with by a Glen Canyon Adaptive Management Work Group.

Ironically, what began in 1981 as the bureau’s desire to produce more peaking power has resulted in turning the dam and powerplant into a near steady-state power producer, with very little peaking power, and certainly less revenue.

In a separate, but similar incident, Regional Director David Crandall of the bureau once told me that, in the early 1970’s, he and his staff had tried to obtain agreement from the Navajo and Ute Tribes to construct another backbone transmission line through their reservations, parallel to the one built in the early 1960’s. To this leaders of both tribes replied firmly, “Absolutely not, but we would like you to remove the line that is already there!” No second line was ever built.

Changing Perceptions About Pre-dam Glen Canyon

From the early 1950’s onward, opposition to having a dam in Glen Canyon has been a factor to consider. During the Congressional hearings of 1954-1956, the opponents were vocal but unorganized, and numbering comparatively few. River running at that time was not a popular sport. Boating parties venturing into Glen Canyon were occasional private parties and sometimes boy scout groups. And of those that did see the main canyon, very few ventured far into the varied and fantastically eroded side canyons. As late as

[21] Steven W. Carothers and Bryan T. Brown, *The Colorado River Through Grand Canyon*, University of Arizona Press, Tucson (1991), p. 149

1955, Katie Lee, Tad Nichols and Frank Wright bestowed names on several previously unnamed side canyons.[22]

Glen Canyon suffered also by the attention given to the Grand Canyon. Whereas Grand Canyon was magnificently huge, astoundingly deep, and almost incomprehensible, "one of the great sights, which every American, if he can travel at all, should see," (Theodore Roosevelt), Glen Canyon was colorful, intimate, and comfortable. The Colorado River in Grand Canyon was lined with threatening river rapids; the same river in Glen Canyon had none. A spur rail line reached the South Rim in 1901 and the first automobile arrived at that point in 1902, but no decent road reached Glen Canyon until 1957. Quite probably, had Glen Canyon not been overshadowed by the public attention given to the Grand Canyon, it would have been much better known when engineers and water managers started talking about a dam.

How indeed is a geological curiosity transformed into a cultural icon? It is not a simple process of "being there." As author Stephen J. Pyne points out Grand Canyon itself was once just a geological curiosity—explorer Joseph C. Ives, writing in 1858, called it a "profitless locality"--but the image of the canyon was gradually transformed by a cadre of scientists, writers, painters, and photographers, including John Wesley Powell, Clarence Dutton, William Henry Holmes, Thomas Moran, and publicity men of the Santa Fe Railroad.

> *Among the last of America's landscapes to be formally explored, the Grand Canyon had become among the first of its natural marvels and, for a nation that tended to substitute natural monuments for cultural ones, entered the pantheon of its sacred places. Its valorization offered as much a cross section through American history as of earth history. The evolution of that interpretation had, with eerie symmetry, mimicked the evolution of the Canyon's features. The spasmodic tectonism of geographic exploration, the varied tributaries that flowed from the main currents of American thought—with breathtaking brevity the two processes had merged, and not merely laid down a course of history but entrenched it so deeply the Canyon became a permanent feature of America's cultural landscape.*[23]

Before the dam, Glen Canyon missed similar scrutiny by scientists as well as by lyric poets and painters. It had been visited by perhaps hundreds of miners and prospectors in the 1890's and again in the 1930's.[24] Yet to most of those who had heard the name at all, Glen Canyon was simply another in a long series of gorges cut by the Colorado River through the Colorado Plateau, probably a good place for a dam.

All of this began to change after construction began on Glen Canyon Dam. Realizing that time was running out to see the canyon, private river boating parties floated

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[22] Lee, Katie, *All My Rivers Are Gone—A Journey of Discovery Through Glen Canyon,* Johnson Books, Boulder, CO, (1998)

[23] Pyne, Stephen J., *How The Canyon Became Grand,*, Penguin Books, New York, (1999), p 114

[24] Crampton, C. Gregory, *Outline History of the Glen Canyon Region,* University of Utah Anthropological Papers #42, Salt Lake City (1959)

through Glen Canyon in increasing numbers from 1956 to 1963, when water storage was initiated in Lake Powell.

One of the most influential member of these boating groups was David Brower, Executive Director of the Sierra Club. Brower, who had not objected to Glen Canyon Dam so long as Echo Park Dam was eliminated from the Colorado River Storage Project in 1956, was astonished by the beauty and variety of Glen Canyon. He soon contracted with photographer Eliot Porter to take color photographs in the canyon, for eventual publication in a Sierra Club book, entitled *The Place No One Knew—Glen Canyon of the Colorado.*[25] The title of the book, which came out in 1963, was of course, a misnomer, since Glen Canyon was historically the most visited of the Colorado River canyons. What the title meant, rather, was that writers, painters, and photographers had never enshrined Glen Canyon sufficiently to make it a cultural icon. Understated in the title was the belief that had the canyon been a cultural icon, such as the Grand Canyon, Glen Canyon Dam would never have been authorized.

After Lake Powell began to form, most media publicity centered on the beauties of the lake and the novelties of boating into narrow side canyons barely wide enough for passage. During the 1960's very little was said about the loss of pre-dam Glen Canyon. Gradually, however, more voices were heard decrying the loss, particularly among young people. Certainly, the loss of confidence in the federal government due to the Vietnam War and Watergate had a pronounced effect, for it caused many, especially those of college age, to question what else the government had done wrong. Also, with new equipment and money, this younger generation was more adventurous than those earlier. Although it would be a mistake to categorize an entire generation, many of them wanted to climb mountains, hike trails, camp out, surf in the waves, and boat down wilderness rivers. To them it was frustrating to learn through books such as Eliot Porter's and several magazine articles of what Glen Canyon used to be. At least some of them felt that older generations had denied to them a moving river and much of the scenery in Glen Canyon, as well as a great adventure—even perhaps, a soul inspiring mystical journey. A slow houseboat trip on Lake Powell—or even on a speedy personal water craft—could hardly compensate. By the early 1980's, these discontented young people were ready to organize against the dam. The vanished Glen Canyon was indeed becoming a cultural icon—even posthumously.

The Drain Lake Powell Movement

A strong and influential voice was added in 1968, when Edward Abbey burst upon the scene with his book *Desert Solitaire—A Season in the Wilderness,*[26] a robust, well-written collection of Abbey's stories from southeastern Utah. New Yorker Magazine called him "a good hater."[27] In describing Lake Powell Abbey wrote:

> *[Where Major John Wesley Powell] and his brave men once lined the rapids and glided through silent canyons, two*

[25] Porter, Eliot, *The Place No One Knew—Glen Canyon on the Colorado,* Sierra Club, San Francisco (1963)

[26] Abbey, Edward, *Desert Solitaire—A season in the Wilderness,* McGraw-Hill Book Co., New York (1968)

[27] New Yorker Magazine, April 6, 1968

thousand feet deep the motorboats now smoke and whine, scumming the water with cigarette butts, beer cans and oil, dragging the water skiers on their endless rounds, clockwise.[28]

Abbey also quipped, "I'm a humanist: I'd rather kill a *man* than a snake!" And one of his visions, supposedly written while Glen Canyon Dam was still under construction, was that "some hero will carry a rucksack full of dynamite into the dam, hide it carefully, then attach blasting caps to the official dam wiring system so that when the dam is dedicated by the President and Secretary of the Interior and Governors from the Four Corner states, a button will be pushed, igniting the "loveliest" explosion ever seen, and the new rapids formed will be named "Floyd E. Dominy Falls" in honor of the chief of the Reclamation bureau."

Desert Solitaire was an immediate best seller and has gone through several editions and reprinting, and is even today, 34 years later, still in print. In 1975, Abbey followed this up with *The Monkey Wrench Gang,*[29] a novel about a small band of self-righteous, do-gooder eco-terrorists who have the dream of destroying Glen Canyon Dam, but who, in the meantime, whet their destructive impulses on power lines, road building equipment, and on the train carrying coal from Black Mesa to the Navajo Powerplant near Page. Again Abbey displayed his writing talent, as well as his iconoclastic view of economic development and what he called "industrial tourism."

These two books by Abbey contributed greatly to the anti-dam movement, both by enhancing the status of the pre-dam Glen Canyon as a cultural icon and by fanning the flames of discontent with the dam and with Lake Powell—which some referred to as "Lake Foul", or, at best, "Reservoir Powell." This said, one could hardly dispute the fact that around three million people visit Lake Powell each year, spending millions of dollars on boats, lodging, food, and supplies. What it does mean rather, is that public perceptions of the lake (or reservoir), were becoming more polarized. Undoubtedly the boating portion of the public loves the lake—it is, of course, one of the most scenic lakes in the world—while a vocal minority now calls for removal of the dam as soon as possible.

On a warm spring day in 1981, Ed Abbey showed up at the dam, ostensibly to act as high priest for a recently organized group calling themselves Earth First! A few of its members climbed over a gate leading to the crest of the dam, then walked to the center point where they began unfurling a tapered sheet of black plastic sheeting 300 feet down the downstream face, meant to represent a terrible crack in the dam. On the bridge, 350 away, Abbey shouted "Earth First—Free the Colorado!" and the seventy or so people that had accompanied him joined in.[30]

The Earth First! mission statement today proudly boasts "Controversial tactics, such as "cracking" dams with banners, blockading bulldozers, sitting in trees, and disabling Earth-destroying equipment ("monkeywrenching"—as one word) were introduced to the modern environmental movement."[31]

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[28] Ibid. p. 152

[29] Abbey, Edward, *The Monkey Wrench Gang,* J.B. Lippincott Company, Philadelphia and New York, (1975)

[30] Martin, Russell, *A Story That Stands Like A Dam—Glen Canyon and the Struggle for the Soul of the West,* Henry Holt and Co., New York (1989)

[31] Earth First web site

Soon after this 1981 incident, the bureau tightened security at the dam. First workmen installed closed-circuit TV cameras at practically all access points. For casual visitors, no longer could they roam freely on a self-guided basis down the elevators and onto the west end of the generator floor, the transformer deck and the governor gallery. They would now have to first obtain a ticket, have all tote bags inspected, and then proceed in small groups accompanied by a bureau guide. Furthermore, accessible areas were reduced by cutting out the governor gallery.

Near Moab, Utah, a few rebellious men and women actually tried their hand at eco-terrorism, monkey wrench style, by chain-sawing down a wooden transmission tower, thereby disrupting power service. The loud public reaction against this act seemed to alert the perpetrators that it was self-destructive behavior, calculated to win no allies. At least twice, studios in Hollywood have seriously considered turning *The Monkey Wrench Gang* into an action filled movie, but each time they have backed away for fear of inspiring copy-cat acts of destruction.

During the 1980's until 1996, protests against the dam seemed to subside, perhaps because of the environmental studies and the preparation of an Environmental Impact Study then underway. The National Environmental Policy Act of 1969, had, however, significantly altered the equation by requiring extensive studies and producing an Environmental Impact Statement prior to authorization. Congressman Wayne Aspinall, who had played such a pivotal role in the campaign for CRSP, was heard to say, in 1981, "We got the CRSP approved just in time. Today we could never get it authorized—particularly if it included Glen Canyon Dam."

Barry Goldwater, set to retire from the Senate in 1986, said that if he could recast one vote in his entire Senate career, it would have been the vote that doomed Glen Canyon.[32]

In 1996, a new group advocating removal of the dam was formed. The Glen Canyon Institute was led by two men: David Wegner, a biologist who had served as director of the environmental studies for the Bureau of Reclamation, and Richard Ingebretsen, a physician in Salt Lake City. In the GCI mission statement is the following:

> *Although in 1996 the Bureau of Reclamation completed an EIS on operations of the dam, decommissioning the dam was not offered as an alternative to the public. Public comments, which suggested decommissioning of the dam, were simply rejected as falling outside the scope of that EIS process. Glen Canyon Institute believes that the American public should decide whether or not the long term environmental costs of maintaining Glen Canyon Dam outweigh the short term benefits provided by Powell reservoir.*[33]

Goal of the GCI is to produce a Citizens' Environmental Impact Statement that would clearly show the benefits of removing, or at least decommissioning, the dam. Based in Flagstaff, Arizona, as of September 2000 the organization reported a membership of 1,400 individuals spread throughout the United States. Richard Ingebretsen readily admits that draining Lake Powell is a long term objective, probably not achievable for at least

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[32] Stiles, Jim, *Why We Should Drain Lake Powell*, Canyon Country Zephyr (April/May 1997)

[33] Glen Canyon Institute, *Citizens' Environmental Assessment (CEA) on the Decommissioning of Glen Canyon Dam,* Interim Report, Glen Canyon Institute, Flagstaff, AZ (Fall 2000)

twenty years, yet he is optimistic that their effort will meet with success. While Ingebretsen and his group mention the economic costs of lake surface evaporation, what they are really striving for is to raise pre-dam Glen Canyon to the status of a cultural icon, just as David Brower had been trying to do since 1963.

Brower, probably the most influential environmentalist in the country, the man who had almost single-handedly defeated Echo Park Dam, was also a member of GCI, and spoke at several of the GCI meetings. On his own initiative in 1997, Brower convinced the national board of the Sierra Club to unanimously declare its support for draining Lake Powell, thus making it national policy.. Subsequently Brower wrote even more articles, gave more speeches, always advocating decommissioning of the dam, while admitting apologetically that he had tacitly supported the dam during the 1950's. Brower died in 2000, but many of his followers in the Sierra Club and elsewhere have vowed to carry on his campaign.

Congressman James Hansen of Utah responded to the movement by calling for a Hearing before his House Interior Committee in September 1997. His primary purpose was obviously to squash the drain Lake Powell initiative in the bud. At that hearing, Sierra Club president Adam Werbach and GCI's Dave Wegner reportedly "took a beating from politicians and experts who dismissed the plan as "loony," "impractical," and "certifiably nutty,"[34] The hearing somewhat backfired in that it only helped to publicize the concept of draining the lake by giving it Congressional and media attention.

To counter the threat from the GCI and the Sierra Club, a group of Page residents, in July 1997, organized what they named Friends of Lake Powell. Its avowed purpose was and is to discount negative claims against the dam and reservoir and to promulgate the recognized benefits.

Some people considered that the methods employed by the Glen Canyon Institute and the Sierra Club were too slow to take effect. A new group was therefore organized in January 2000, with more radical tactics in mind. The Glen Canyon Action Network, (GCAN), headquartered in Moab, espouses public demonstrations, but not eco-terrorism at the dam or wherever it can obtain media attention. When the GCAN's announced that its first rally would be held at the dam on March 14, 2000, the Friends of Lake Powell countered that they would hold a demonstration at the same time and place, which to the bureau threatened a possible riot. When the day arrived local police were on hand to separate the groups by the width of the canyon, one on one side, one on the other. Separate demonstrations and speeches were then forthcoming, one group promoting draining the lake and one against it. Visitors standing on the bridge separating the two demonstrations were watched closely by the police. No trouble (other than loud P.A. systems) was reported.

In the future we can look forward to sustained opposition to continued operation of Glen Canyon Dam, restricted though it has been. And Lake Powell will continue to provide a Mecca for fishers, boaters, and water oriented sports. Considering the economic investment in the dam and powerplant, in the city of Page, in recreation facilities around Lake Powell, and in the Navajo Generating Station, which draws clean cooling water from the lake, it is not likely that the drain Lake Powell movement will have success, at least not

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[34] Hanscom, Greg, *Reclaiming a Lost Canyon,* High Country News, Paonia, CO, (November 10, 1997)

for several decades. Emphasizing the need for continued operation of both Glen Canyon Powerplant and the Navajo Generating Station is the current, and probably long term, demand for additional electrical energy in the western United States.

Sedimentation

Emergencies--or at least urgent considerations--occur at the dam at irregular intervals, ranging from floods to worn out equipment, and are handled competently by the well-trained maintenance staff. One problem that the staff is not equipped to handle, the one that may eventually doom first Lake Powell and eventually the dam itself, is *sediment.*

All rivers carry some sediment, but where the land is heavily vegetated, as in the northern part of the Upper Colorado Basin, the waters run fairly clear. Yet as the river descends toward the southwest, picks up tributaries that enter from arid and semi-arid lands, soils of which usually remain stable, sometimes for years, as if waiting for the wet touch of rainfall. Yet when the rain does arrive it is often strikes suddenly as a gully washer, a cloudburst that seems to tear the top of the land, sending it in a turbid brown torrent toward the master river, the Colorado. Scientists call these wildly destructive floods bv the term “debris flows.”

Geologically speaking, it was the periodic debris flows pouring into the Gulf of California that formed a huge natural dam that now separates the Gulf from the Imperial Valley of California.

Of all the rivers and streams flowing into Lake Powell, the heaviest sediment laden is the San Juan River and its tributaries, particularly in its western region. For over a century pioneers have tried to irrigate along its banks, but their dams have washed out, their ditches filled with sand, and their fields ruined by briefly rampaging water. Most of the farmers of Bluff, Utah, have moved away, defeated by the unruly San Juan.

Since 1963, of course, all of that sediment has collected in Lake Powell, and continues to do so.

Sediment settles in the upper parts of the lake, diminishing its reservoir’s storage capacity and its ability to meet downstream commitments during times of drought. The San Juan River arm of the lake is already heavily clogged. The San Juan Marina on that arm had to be closed in 1988 due to heavy sedimentation. In the early 1990’s a sediment bar built up so firmly on the San Juan arm that it blocked the inflow from the river, forcing the water to rise up, flow across a section of flat sandstone, then drop by a 20-foot waterfall into Lake Powell. Although spring flood waters eventually washed out the dam, the accumulating sediment is advancing upstream, even higher than the lake, causing great distress for river boating parties.

Even on the Colorado arm of the lake the sediment stretches all the way from the high water mark, almost 60 river miles down to the mouth of the Dirty Devil, where is appears ready to create a small waterfall of its own..

Early in my career with the Bureau of Reclamation, a prescient river runner named Art Gallenson visited me to ask if anyone had ever considered drilling a one-hundred mile sediment conveyance tunnel from the upper part of Lake Powell to the canyon below the dam. In my naivety I thought his idea was ridiculous. So also did BuRec officials in 1994 when they commissioned the Environmental Impact Statement study of the effects of the dam's operation on the Grand Canyon. So no tunnel was seriously considered.

No one knows when sediment will reach the dam, but it will not be soon. Anticipating that eventual day, bureau engineers are considering using the outlet tubes to flush some of that sediment around the powerplant.[35] A study of sedimentation rates by the bureau showed that it would be 700 years before sediment would reach the penstock level, elevation 3,590, where water is drawn into the turbines. Although the powerplant could, and probably will, generate power up till that time, no official prediction has been made as to when the reservoir will be too small to meet downstream commitments—or when Lake Powell is so diminished in size that water oriented recreation is no longer practical. Perhaps by then the drain Lake Powell movement will have finally achieved success and the stored sediment will be somehow passing around or through the dam, through the Grand Canyon, and filling up any remaining capacity in Lake Mead.

Conclusions

The bumpy road that Glen Canyon Dam history has taken in the past 48 years represents a long encounter with scenic values, with cultural antiquity, with natural processes of flood and sedimentation, and with preservation of two national icons, the Grand Canyon and Rainbow Bridge. The very rust-red sandstone landscape that backdrops Lake Powell, making it one of the most scenic bodies of water in the world, is the same scenery that causes environmental groups to demand that the lake be drained so that more of that scenery can be seen and accessed. Those opposed to the dam will continue to promote pre-dam Glen Canyon as a national and cultural icon that should be returned from the depths—the sooner the better. But they will have little success so long as investments in the dam and lake recreation remain both widespread and profitable. When the day arrives that maintenance of the dam no longer makes economic sense—no matter how far in the future that may be--Glen Canyon Dam will strike the biggest bump of all. We can only guess what future generations will do with the dam and with a huge sediment-filled reservoir at that time.

[35] Randy Peterson, Bureau of Reclamation Adaptive Management Engineer, address to Bureau of Reclamation retirees, 2000

Impact of Reclamation's Hydraulic Laboratory on Water Development

Philip H. Burgi [1]

ABSTRACT

The paper covers the history of Reclamation's hydraulic laboratory from its inception in 1930 at Colorado Agricultural Experiment Station, Fort Collins, Colorado to the present. Emphasis is placed on the laboratory's historical role in developing new design concepts for hydraulic structures to meet Reclamation's ever-increasing challenges over the past seventy years.

The paper presents the design challenges associated with specific structures such as: Hoover Dam side channel spillway, Grand Coulee Dam spillway bucket, Hungry Horse Dam tunnel spillway, and more recently the aeration slot design developed for Reclamation's tunnel spillways to prevent cavitation damage.

During the 1950's and 1960's Reclamation's hydraulic laboratory initiated an extensive research program to develop standard designs that eventually led to engineering monographs and manuals coauthored by hydraulic laboratory staff. The paper concludes with the hydraulic design challenges facing Reclamation in the next century. The water management issues associated with fish passage and water conservation as well as infrastructure security at numerous dams in the western U.S. are some of the hydraulic challenges in Reclamation's future.

BACKGROUND

The Bureau of Reclamation was established in 1902. In its first ten years eighteen dams were built. By 1930 fifty dams had been constructed. The first irrigation projects were fairly simple, consisting of a diversion dam, headworks, canals, and turnouts. These early projects involved no special challenges other than those peculiar to each site. To optimize water basin development, dams of increasing height were required and their design and construction created new problems and provided serious challenges for Reclamation's engineers.

The 1906 Congress introduced the function of hydropower when it authorized the sale of excess power generated at Reclamation projects. In 1928 Congress passed the Boulder Canyon Project Act (The name Boulder Dam was changed to Hoover Dam April 3, 1947 by joint congressional resolution). This act inaugurated a new era in the conservation and utilization of western water. Hoover Dam would be the principal structure of the Boulder Canyon Project and would introduce a new concept in western water development referred to as multi-purpose development. Other projects soon followed: the Central Valley Project, Columbia Basin Project, Colorado-Big Thompson Project, and the Missouri River Project. These multi-purpose projects optimized utilization of water and land resources in large areas of entire river basins. Rhone[1] states the quarter century between 1948 and 1973 was especially productive when more than half of Reclamation's dams were constructed.

THE EARLY YEARS

In the early years before 1930, many of Reclamation's design engineers were recruited from Reclamation's parent organization, the U.S. Geological Survey. The

[1] Founding Member EWRI of ASCE, Water Resources Consultant, Wheat Ridge, Colorado,

supervisory staff of the design units maintained extremely high engineering standards for their personnel. Typically, each design leader assembled and maintained a design manual based on their training and experience; these informal manuals were passed on to subordinates who, in turn, added to the standards and through their new knowledge and experience became even better qualified designers.

When Reclamation completed the construction of Shoshone Dam (100 m) in Wyoming in 1910, it was the highest dam in the world. In the next 25 years Reclamation held this record three more times with the construction of Arrowrock Dam (106 m) in Idaho in 1915, Owyhee Dam (127 m) built in eastern Oregon in 1933, and finally Hoover Dam (221 m) on the Colorado River in 1936.

RECLAMATION'S HYDRAULIC LABORATORY

Reclamation's hydraulic laboratory was established in the early 1930s expressly to solve the technical challenges presented in the design of these large structures. With the anticipation of designing Hoover Dam there came the recognition that this structure would impose design and construction challenges well beyond the textbooks and experience of the day. The tremendous construction costs associated with these large structures required careful attention to the preliminary design and required hydraulic model testing before one could finalize design and start construction.

Although the name "hydraulic laboratory" is relatively modern, the concept has been around for a long time. Scholars as early as Leonardo da Vinci recognized the importance of experimentation when dealing with the flow of water. He is quoted as saying, "Remember when discoursing on the flow of water to adduce first experience and then reason". [2] The purpose of the hydraulic model is to use the tool of similitude to demonstrate the behavior of flowing water at reduced scale. Typically, models are used to study rivers and waterways of hydraulic structures and equipment such as: spillways, outlet works, stilling basins, gates, valves, and pipes associated with large dams. Agreement between model and prototype has proven very satisfactory. [3, 4]

At the turn of the 20th century, some European universities and especially universities in Germany recognized the value of experimental model studies to solve hydraulic challenges such as those posed by dam spillways and outlet works, siphons, tunnel inlets, and bridge constrictions on rivers. John R. Freeman (1855-1932), a hydraulic engineer from the United States, felt very strongly that we should develop similar hydraulic laboratories to those being utilized in Europe. In 1924 he visited laboratories in Berlin, Dresden, Brunn and Karlsruhe. He had a significant influence on the development of hydraulic laboratories in the United States. Freeman writes in 1929, *"Nowhere, yet, in America has the writer found the acceptance and reliance upon the doctrines of similitude which he has found at substantially all of the great European engineering universities, and which have been developed there wholly during the past 30 years, and mainly during the past 10 years.*" [5]

Beginning in the early thirties, laboratory activity in engineering schools in the United States greatly increased. Freeman describes some of the early work conducted in laboratories in the United States: Cornell University (1899), State University of Iowa (1919), Alden hydraulic laboratory of the Worcester Polytechnic Institute (1910), and several commercial laboratories conducting experimentation with hydraulic turbines. Eventually, hydraulic laboratories were established in government facilities such as the Miami Conservancy District in Ohio, the U.S. Bureau of Standards, U.S. Army Corps of Engineers, Soil Conservation Service, and the U.S. Bureau of Reclamation.

Figure 1. 1931 Photo of Reclamation Hydraulic Laboratory staff at Fort Collins

Investigations with hydraulic models had their start in the Bureau of Reclamation in August 1930 when thirteen engineers, technicians, and craftsmen from the Denver Reclamation Office began working in the hydraulic laboratory of the Colorado Agricultural Experiment Station in Fort Collins, Colorado. The 242 m^2 laboratory was built in 1912 under the direction of Ralph Parshall.

By 1935, the laboratory in Fort Collins had expanded to four times its original size to handle the ever-increasing Reclamation work load. One of the early studies was for the proposed shaft spillways for Hoover Dam. As a result of these studies a change was made from the original shaft spillway concept to two side-channel spillways to accommodate the design flow that had increased from 5,670 to 11,340 m^3/s.

In the summer of 1929, Emory Lane was appointed as engineer in charge of the Bureau of Reclamation's of hydraulic, sediment, and earth materials research studies. A graduate of Purdue and Cornell Universities, he worked for the Miami Conservancy District, Ohio before coming to Reclamation. During his 6-year period as administrator of the hydraulic laboratory, Lane initiated the comprehensive laboratory investigations undertaken for Hoover Dam, Grand Coulee Dam, Imperial Dam and de-silting works and the model studies of the All American Canal structures.

Jacob Warnock, another graduate of Purdue**,** came to Reclamation as an associate hydraulic engineer after working with the Corps of Engineers in their Chattanooga, Nashville, and Huntington offices. By 1934 Warnock, became head of the hydraulic laboratory in Fort Collins when Emory Lane moved to Denver to direct a small hydraulic laboratory that had been set up in the basement of the Old Custom House in Denver. Victor Streeter, who later became a renowned Professor of Hydraulics at the University of Michigan, was one of the staff members in Denver during this period.

Figure 2: Jacob Warnock (front right) with visiting engineers in the Custom House Laboratory

In a summary article written in 1936, Warnock stated, "*Models were first used extensively by the Bureau in 1930 in the design of the spillway for the Cle Elum Dam of the Yakima project in Washington. The design of the spillways for Boulder Dam, Madden Dam in the Panama Canal Zone, and Norris and Wheeler dams for the Tennessee Valley Authority, served as stepping stones in further developing the technique and improving the methods*."[6]

Warnock was a strong believer in the value of hydraulic model investigations. "*The procedure by which models of hydraulic structures are built and tested in the laboratory before the design is finally adopted and committed to construction is analogous to the manner in which a newly designed machine is thoroughly inspected for defects and imperfections at the factory. The models reveal undesirable features of the design and indicate the proper means for the correction.*" [7]

By 1935 Jacob Warnock became head of the laboratory in Denver and was instrumental in its move to the New Custom House in 1937 where there was approximately 475 m^2 available for studies.

The work of the laboratory became so prolific that Reclamation tested 80 models in the period from 1930-38 and had 50 engineers, technicians, and craftsmen working in three laboratories. "*The use of models has proved so advantageous in indicating opportunities for reducing costs and improving hydraulic properties that* *the work of the laboratories is now recognized as a regular part of hydraulic design. At the present time, the three laboratories are engaged in testing or constructing models of twenty different features relating to ten major projects*." [7]

In the fall of 1938, Reclamation discontinued its work in the Fort Collins laboratory. Warnock figured prominently in the design of the hydraulic features of Hoover, Grand Coulee, Shasta, Friant, and many other large dams and irrigation projects in the west. His untimely death in December 1949 at the age of 46 was a great shock to Reclamation's Denver Center.

The wartime westward shifting of population and industry created an impetus and need for a Reclamation construction program much larger after the war than it had been before. By 1943 Reclamation organized into seven regional areas based on large watersheds in the West and established a Chief Engineer's Office in Denver responsible for all design and construction. The small laboratory space in the New Custom House was inadequate for the enlarged program. Sufficient space was available at the former Denver Ordnance Plant (Remington Small Arms Plant) located on the west side of Denver and now referred to as the Denver Federal Center (DFC).

In the later part of 1946, the hydraulic laboratory was moved to its present home in the Denver Federal Center where it occupied some 4925 m^2 of laboratory space. At the time, Reclamation's staff at the Denver Federal Center totaled over 2240 employees. These facilities were unequaled in their specialized qualifications anywhere in the world. Design and construction engineers worked in tandem with experts in hydraulics, concrete, soils, chemical, and other laboratories to meet the new challenges of water development in the arid west.

A quote from the July 1950 edition of The Reclamation Era states, "*The combination of men and laboratory equipment is paying huge dividends to the public. Water and power users, who ultimately pay for Reclamation projects, pay for the work of the Branch of Design and Construction. They should be reassured to know that economies in construction discovered at the Center have more than paid for its total operating costs, as well as the entire cost of establishing and equipping it. Many of the money-saving techniques and materials conceived in connection with specific construction works will apply as well to later works, thus compounding the monetary economies*." [8]

There were other hydraulic laboratories developed and used by Reclamation. They were primarily field laboratories located at: Montrose, CO (1931-1936), Grand Coulee Dam (early 1940s), Hoover Dam (1939-1945), Estes Park Colorado Powerplant (late 60s and early 70s).

LABORATORY CONTRIBUTIONS

Spillways

Spillways at dams are used to pass the design flood and thus protect the dam from overtopping. Early in Reclamation history there were five general categories of spillways in use: "glory hole" or shaft-type (Gibson Dam), side-channel (Hoover Dam), overflow type (Grand Coulee), open chute type (Bartlett Dam), and enclosed tunnel chute (Seminole Dam).

The importance of adequate spillway design cannot be overemphasized.

Operating experience with spillways for dams has revealed problems of two types: (1. inadequate capacity, and (2. unsatisfactory performance for design or less-than-design discharges. Historically, Reclamation has taken a very serious position toward adequately studying spillway performance before going to final design.

One of the first major impacts resulting from hydraulic laboratory studies was the major improvement in spillway capacity resulting from the replacement of the planned glory-hole spillway design for Hoover Dam spillways with the side-channel spillway that ultimately provided the desired spillway capacity.

These early model studies were conducted at Ft Collins and Montrose as well as the Custom House in Denver. The large 1:20 scale outdoor model at Montrose was used to finalize the design of the drum gates on the side-channel spillways at Hoover Dam (total spillway capacity of 11,340 m^3/s) replacing the proposed Stony gates, which proved to be unsatisfactory during the model tests. A total of eight models were used in the hydraulic design of Hoover Dam with model scales of 1:20(2), 1:60(3), 1:64, 1:100, and 1:106.[9]

Four models were used in the design of Grand Coulee Dam ranging in scale from 1:30 to 1:184. A major improvement in the design for Grand Coulee Dam was the replacement of a proposed large hydraulic jump stilling basin with a roller bucket to dissipate the energy at the toe of the Grand Coulee spillway designed to pass 28,325 m^3/s. A construction savings of $4,750,000 (1941 costs) resulted from use of the roller bucket energy dissipator developed in Reclamation's hydraulic laboratory. [8]

Reclamation's high dam tunnel spillways proved to be a very economical means to pass large flood discharges in lieu of building large capacity surface spillways and stilling basins on the dam abutments. However, as early as the winter of 1941 when the Arizona tunnel spillway at Hoover Dam operated for 116 days there was suspicion of the vulnerability of concrete to damage caused by high velocity flow in tunnel spillways.[10] This spillway operation resulted in a large hole in the tunnel spillway elbow 14 m deep, 9 m wide and 35 m long. The damage was thought to initiate at a "misalignment" of the tunnel invert just above the elbow. The damage was caused by high velocity flow passing over the roughness and leading to bubble formation (similar to boiling water) in the flow. When the bubbles collapsed, high energy shock waves were generated damaging the concrete. This phenomena is referred to as cavitation formation and damage. In the 1940's the damage was repaired by backfilling with river rock and then covering with a thick layer of high quality concrete. The concrete surface had a very fine finish, almost terrazzo, to prevent reoccurrence of the cavitation. Tunnel spillways were later constructed at Yellowtail, Flaming Gorge, Blue Mesa, and Glen Canyon Dams.

The cavitation damage problem surfaced again in June and July 1967 when the tunnel spillway at Yellowtail Dam discharged for 20 days at 425 m^3/s. By July 14 it was evident that there was a problem in the tunnel spillway. When drained and inspected a hole 2 m deep, 6 m wide and 14 m long was discovered. In earlier laboratory investigations, the introduction of as little as 7.5% air into the water flow eliminated damage associated with cavitation on concrete surfaces.[11] In 1967, Hydraulic laboratory studies on a 1: 49.5 scale model of the Yellowtail Dam tunnel spillway resulted in design of an aerator located some distance upstream of the elbow consisting of a 760 mm high ramp that extended above the springline of the tunnel and provided air to the underside of the high velocity jet traveling through the tunnel.

The first installation of an aerator in a tunnel spillway was at Reclamation's Yellowtail Dam.[12]

In 1983, high runoff in the Colorado River basin created the need to pass flood flows through tunnel spillways at Blue Mesa, Flaming Gorge, Glen Canyon, and Hoover Dams. The resulting damage was so extensive at Glen Canyon Dam's two tunnel spillways that $42,000,000 (1985 costs) and a year of reconstruction was required to repair the spillways and install an aerator in each tunnel.[13] Reclamation conducted extensive laboratory model tests to determine hydraulic performance of the aerators at these tunnel spillways.

Figure 4. Damage to Glen Canyon Dam left spillway in 1983.
The "big hole" was 11 meters deep.

By 1985 aerators were installed in all five of these high head tunnel spillways in the western United States. The left tunnel spillway (Arizona side) at Hoover Dam experienced cavitation damage in 1983 and had to be repaired with an aerator added despite the smooth surface placed in 1943. Henry Falvey wrote a comprehensive engineering monograph summarizing Reclamation's experiences and developments in cavitation damage control entitled, *Cavitation in Chutes and Spillways*.[14] This publication was yet another of the numerous documents produced by the hydraulic laboratory staff to assist in the design of water projects.

Sediment Control Structures at Diversion Dams

In the period from 1950-1965 numerous model studies were used to develop sediment control measures at diversion dams.[15] To develop the most satisfactory solution of a sediment control problem at a diversion usually requires a "movable bed" hydraulic model study. Structures and techniques such as curved guide vanes, short tunnel under sluices, and vortex tubes were developed in the laboratory to exclude sediments. On large projects such as the All-American Canal, large settling basins were developed and built. However, the cost of these large structures was prohibitive for many of the diversion dams across the Plains States. More economical solutions were often developed which included a simple gated sluiceway and using some of the water as a means to bypass the sediments around the diversion intake structure.

Gates and Valves

It was clear in the 40's that as the size of dams and reservoirs increased, for economic reasons it became necessary to design projects for multiple use, such as flood control, irrigation, power development, and river regulation for navigation. The rigorous demands imposed by such multiple use of a storage dam required that the outlets be designed to give close regulation of the rate at which stored waters were released. The increase in dam height lead to higher pressures and velocities and in many cases the need for larger capacity outlets. Many improvements in the mechanical design of gates and valves were made to meet the challenge of these new conditions. However, most gates and valves were designed for simple open or closed operations. Regulation in some cases was made by providing numerous outlets controlled by gates such as those used at Grand Coulee Dam where increase or decreases could be made in finite increments equal in value to the capacity of a single outlet. Most valves developed prior to the 1930's were designed for pressure heads up to 130 m, totally inadequate for the new dams proposed.

The Hoover Dam tunnel-plug outlets provided the most outstanding challenges. Each tunnel had six – 1830 mm needle valves under pressure heads up to 171 m which discharge up to 623 m^3/s into a 15 m diameter concrete tunnel. The laboratory model studies included tests at scales of 1:106, 1:60, and 1:20 to assure the validity of the design against any scale effects. The final configuration selected represented a distinct improvement over those originally proposed. The laboratory tests also showed that large air vent tunnels originally proposed were not necessary resulting in construction savings of $30,000 (1932 costs).[16] There were several occasions in the 1980's where the old internal differential needle valves failed during uncontrolled closure. In some cases, these uncontrolled closures resulted in loss of life. In the early 1990's Reclamation undertook additional studies to replace all of their needle valves across the West. The needle valves were soon replaced with large jet flow gates developed by Reclamation in the late 40's for Shasta Dam.

The preferred large valves for Reclamation dams were the needle valves (1909-1942) and the hollow jet valves (1950-1967). Over the years, Reclamation has upgraded outlet gates and valves from the early Ensign valves (1905-1915), to needle valves (1909-1942), to tube valves (1941-1945), to hollow-jet valves (1950-1967) and jet-flow gates (1945-67). James Ball, Donald Colgate and Donald Hebert were three key hydraulic laboratory contributors to Reclamation’s work in the development of high-head outlet gates.[17] A 1973 American Society of Civil Engineering article gives a summary of some of these gates and valves and their installations across the United States.[18]

Hydraulic Laboratory Techniques

In 1955 hydraulic laboratory personnel published Engineering Monograph No.18 entitled *Hydraulic Laboratory Practice*. It was prepared as an aid in applying engineering knowledge and experience to hydraulic laboratory studies. Emphasis was placed on the basic principles of similitude; techniques of model design, construction, and operation; equipment; and field studies. The volume which has been used in hydraulic laboratories world-wide was updated in 1980 on the golden anniversary of the Bureau of Reclamation's first hydraulic model tests.[19]

Stilling Basins and Energy Dissipators

Although hundreds of stilling basin and energy dissipating devices have been designed and built for spillways, outlet works, and canal structures, it is often necessary to make model studies of individual structures to be certain that these will operate as anticipated. In the early 1950's a ten-year laboratory research effort was undertaken to develop general design criteria for stilling basins and energy dissipators. Existing information was gathered from laboratory and field tests collected from Reclamation records and experiences over a 23-year period. Hundreds of additional tests were conducted using six laboratory test flumes. The largest flume was 102 mm wide, 24 m long with an available height of 5.5 m and a discharge capacity of 800 l^3/s. Tests included hydraulic jump stilling basins, short stilling basins for canal structures and small spillways, wave suppressors for canal structures, sloping apron stilling basins, slotted and solid bucket energy dissipators, baffled apron drops, tunnel spillway flip buckets, and test to size riprap downstream of stilling basins. This effort conducted solely in Reclamation's hydraulic laboratory and supervised by Alvin Peterka, resulted in the world renowned Engineering Monograph No. 25 entitled, *Hydraulic Design of Stilling Basins and Energy Dissipators* [20], which has been used for many years as a standard for such hydraulic structures world-wide.

By the 1970s the trend for spillway terminal structures had returned to the flip bucket - the principle used was to direct the flow away from the structure and downstream a sufficient distance where the water could erode its own plunge pool or discharge into a pre-excavated plunge pool. Devices such as a combined hydraulic jump/flip bucket were used for the tunnel spillway at Yellowtail Dam and the surface spillway at McPhee Dam. The energy is dissipated within the basin at the end of the tunnel spillway up to a predetermined discharge where the jump flips out and the structure acts as a flip bucket for larger discharges. Most of the tunnel spillways previously mentioned terminate with flip buckets designed based on various hydraulic model studies in the 50's and 60's.

A device called a baffled apron drop was developed in the laboratory primarily for use on canals as a drop structure at wasteways. In the late 1970's laboratory staff started looking at the baffled apron drop as a spillway structure for dams. In the 80's many baffled apron drops were used as spillways on several Reclamation dams as well as for the States of Washington, New Mexico and Nevada (Conconully Dam, Truth or Consequences Dam, Marble Bluff Dam).

THE HYDRAULIC LABORATORY IN THE 21st CENTURY

At the beginning of the 21st century, Reclamation continues to use the laboratory facilities at the DFC, however there have been many changes over the past 70 years. There are new and improved microprocessor laboratory controls. An ozonator system has been installed to improve water quality and provide for longer use of recirculated water. There have been giant strides in electronic control and measurement as well as increased use of hybrid modeling where numerical and physical modeling techniques are brought together to better understand fluid mechanics. Skilled craftsmen who build the intricate models have always been part of the laboratory staff and continue to play a key role in laboratory studies.

Reclamation's hydraulic structures and equipment investigations and development in the period from 1930 through the 1970's resulted in world class technological advancements in water-resource development. However by the latter quarter of the 20th century, a major paradigm shift had occurred with water development in the United Sates. As public values shifted toward more environmental sensitivity, water agencies changed their focus from an emphasis on *water development* to *water management*. Reclamation's hydraulic laboratory program maintained a contemporary focus throughout these changes over time. The new focus led to an emphasis on developing improved technologies for **(1.** *protecting the public and existing water infrastructure*, **(2.** *encouraging water-use efficiency*, and **(3.** *emphasizing environmental enhancement on regulated river systems*. [21]

In the area of water infrastructure protection, Reclamation's hydraulic laboratory has played a key role in the development of cost-effective spillway designs focused on dam safety issues. Alternative spillway designs, fuse plug concepts, and overtopping protection concepts have been tested and developed. Laboratory research on the labyrinth spillway concept produced design criteria that were applied to the 14 cycle labyrinth spillway for Ute Dam in New Mexico.[22] The labyrinth spillway resulted in construction savings of over $24,000,000 (1982 costs) compared to a traditional gated structure at Ute Dam.[21]

Another alternative spillway design gaining acceptance in the engineering community is the fuse plug concept. Reclamation's hydraulic laboratory advanced the science and acceptance of fuse plugs now used at several Reclamation dams.[23] The construction savings realized by using fuse plugs for additional spillway capacity for Horseshoe and Bartlett Dams on the Verde River in Arizona were in the range of $150-300 million (1984 costs).[21]

Stepped spillway design criteria developed in Reclamation's hydraulic laboratory played a pivotal role in its world-wide acceptance in the 1990's. Stepped spillways are very compatible with Roller Compacted Concrete (RCC) construction and provide an economical spillway when constructed as an integral part of the dam. Hydraulic model studies of stepped spillways for McClure, Milltown Hill, Stagecoach, and Upper Stillwater Dams in the late 1980's were critical in defining energy dissipation characteristics and hydraulic performance of this new concept.[24]

Another recent advancement has been the protection of embankment dams during overtopping occurrences. Studies performed in Reclamation's hydraulic laboratory as well as tests performed in a large-scale outdoor overtopping facility at Colorado Sate University have proven the viability of 305 mm wide, 51 mm high, and 610 mm long concrete blocks to protect the surface of an embankment**.** [25]

Water-use Efficiency continues to play an important role in Reclamation's program. The Western United States depends on a water storage and delivery system built over the past 150 years to provide water for irrigated agriculture, municipal and industrial use, power generation, and recreation. Population growth and environmental water requirements place additional demands on a limited supply and require managers to look for water-use efficiencies. In response to this reality, the hydraulic laboratory has placed increased emphasis on conservation technologies. The ability to measure discharge in open channels on Reclamation projects has been dramatically improved in the last twenty-five years by the development, in cooperation with Agricultural Research Service, of the long-throated flume and broad-crested weir measurement methods as well as other technologies that are robust, low cost and accurate.

In 1953 Reclamation's hydraulic laboratory produced the first edition of the *Water Measurement Manual*. It was compiled from Reclamation's Manual for Measurement of Irrigation Water published in 1946. A second edition was published in 1967. The most recent edition published in 1997 still emphasizes the basics of water measurement but is updated to include the latest measurement technologies.[26] It is also available at: **http://www.usbr.gov/pmts/hydraulics_lab/.**

In addition to water measurement, the laboratory staff has worked for over thirty years in development of water system automation technologies. Reduced cost and increased capabilities of sensors, computer hardware, software, and data telemetry systems have brought practical canal automation capabilities within reach of the majority of water and irrigation districts in the western United States, including many smaller and older districts that still operate their systems using the same methods used decades ago**.**

Future water development will be closely linked with *environmental enhancement* as Reclamation continues to play a role in providing a high standard of living while protecting environmental resources. Historically, Reclamation has had a concern for the natural environment especially as it may impact fish and wildlife resources. In the late 1950's Reclamation's hydraulic laboratory staff assisted with the development and field and laboratory testing of a pilot fish screen structure constructed in the headworks of the Tracy Pumping Plant.[27]

More recently, several fishery and stream restoration projects have built on this earlier experience and illustrate this new enhancement approach. To improve the winter-run Chinook salmon population in the Sacramento River, the laboratory initiated an aggressive research study to develop temperature-control curtains in reservoirs such as Lewiston and Whiskeytown Lakes.[28] The use of this new temperature-control technology, as well as the steel shutter structure at Shasta Dam, has increased the selective withdrawal capability within the Sacramento River basin and improved the management of the river temperature by several degrees and greatly improving the habitat for anadromous fish species. The laboratory has also been involved in retrofitting several Reclamation dams to provide selective withdrawal capability: Shasta, Lewiston, Whiskeytown, Hungry Horse, and Flaming Gorge Dams.

Within Reclamation a bioengineering focus (biological science and engineering) has led to new, innovative concepts for using hydraulic structures to manage regulated water systems in the West. This cooperation of hydraulic engineering and biological sciences in recent years has produced innovative technologies for fish screening, fish separation and handling, and fish passage upstream and downstream at dams and diversion works. These research efforts and experiences will soon be published as a Reclamation fisheries manual. On many Reclamation projects these advancements have been crucial to maintaining water deliveries while also providing new environmental benefits.

SUMMARY

The history of Reclamation's hydraulic laboratory is a story of engineers, technicians and craftsmen who have had an attitude and work ethic best characterized by their persistent high quality work used to tackle the challenges of water development in the West. To some degree, they were exceptional individuals but for the most part their greatest achievements resulted from their ability to work as a team. Although some individuals have been mentioned in this paper, one needs to recognize that the greater gains were almost always the effort of a team. There are many excellent engineers on the present staff who no doubt will become part of the great legacy of Reclamation's hydraulic laboratory. Future generations will make those judgments. Suffice to say, that Reclamation and the nation have benefited greatly by the productivity of the hydraulic laboratory staff over the past seventy years. There are new challenges facing today's laboratory engineers and scientists and their responses to these challenges will define the future legacy of the laboratory.

REFERENCES

1. Thomas J. Rhone, 50th Anniversary of the Hydraulics Division 1938-1988, ed. Adnan M. Alsaffar (ASCE, 1990), 132-147.

2. Gunther Garbrecht, ed., Hydraulics and Hydraulic Research A Historical Review- International Association for Hydraulic Research 1935-1985, A.A.Balkema/Rotterdam/Boston/1987.

3. "Conformity Between Model and Prototype in Hydraulic Structures", Transactions, American Society of Civil Engineers, Vol 109, pg 3-193.

4. Philip H. Burgi, ed, Model-Prototype Correlation of Hydraulic Structures, Proceedings of the International Symposium, American Society of Civil Engineers, August 9-11, 1988. Pp 1- 480.

5. John R. Freeman, ed., Hydraulic Laboratory Practice, The American Society of Mechanical Engineers, 1929, 1-4, 17, 28-32, 697-742.

6. Jacob E. Warnock, "Experiments Aid in Design at Grand Coulee", Civil Engineering, November 1936, pp.737-741.

7. U.S. Department of the Interior, Bureau of Reclamation, Dams and Control Works, February 1938, 205-212.

8. U.S. Department of the Interior, Bureau of Reclamation, The Reclamation Era, February, 1941, 29-32 and July 1950,127-128.

9. Boulder Canyon Project Final Reports, U.S. Department of the Interior, Bureau of Reclamation, Part VI- Hydraulic Investigations, Bulletins 1-3, 1938.

10. Keener, "A Challenge to Hydraulic Designers", Engineering News Record, November 18, 1943.

11. A. J. Peterka, "The Effect of Entrained Air on Cavitation Pitting", Proceedings of the Joint Meeting of the International Association for Hydraulic Research, ASCE, Minneapolis, MN, August 1953.

12. D. Colgate, "Hydraulic Model Studies of Aeration Devices for Yellowtail Dam Spillway Tunnel", U.S. Department of the Interior, Bureau of Reclamation, REC-ERC-71-47, 1971, 13.

13. P.H. Burgi and M.S. Eckley, "Repairs at Glen Canyon Dam," Concrete International: Design and Construction of the American Concrete Institute, March, 1987, pp. 24-31.

14. H.T. Falvey, Engineering Monograph No. 42 Cavitation in Chutes and Spillways, U.S. Department of the Interior, Bureau of Reclamation, 1990, 145.

15. Enos J. Carlson, "Laboratory and Field Investigations of Sediment Control Structures at Diversion Dams", Ninth Congress on Irrigation and Drainage, International Commission on Irrigation and Drainage, Moscow, 1975.

16. Engineering News Record, "Hoover Dam Number", December 13, 1932.

17. D.J. Hebert and J. W. Ball, "The Development of High-Head Outlet Valves", Report on Second Meeting, Appendix 14, International Association for Hydraulic Structures Research, Stockholm, Sweden, June 6-7, 1948.

18. Cortland C. Lanning, "High Head Gates and Valves in the United States", Journal of the Hydraulics Division, ASCE, Vol. 99, No Hy 10, October, 1973, pp. 1727-1775.

19. J.C. Schuster, ed., "Hydraulic Laboratory Techniques", U.S. Department of the Interior, Bureau of Reclamation, 1980, 208.

20. A. J. Peterka, Engineering Monograph No.25 Hydraulic Design of Stilling Basins and Energy Dissipators, U.S. Department of the Interior, Bureau of Reclamation, 1964, 217.

21. Philip Burgi, Issues and Directions in Hydraulics , eds. Tatsuaki Nakato and Robert Ettema A.A.Balkema/Rotterdam/Brookfield/1996,187-198.

22. K.L. Houston, "Hydraulic Model Study of Ute Dam labyrinth Spillway", U.S. Department of the Interior, Bureau of Reclamation, GR-82-7, August, 1982, pp 41.

23. C.A. Pugh, "Hydraulic Model Studies of Fuse Plug Embankments", REC-ERC-85-7, December, 1985.

24. Kathleen L. Houston and Alan T. Richardson, "Energy Dissipation Characteristics of a Stepped Spillway for an RCC Dam", International Symposium on Hydraulics for High Dams, Beijing, China, November 15-18, 1988.

25. Kathleen H. Frizell and Brent W. Mefford, "Designing Spillways to Prevent Cavitation Damage", Concrete International: Design and Construction of the American Concrete Institute, May, 1991, pp. 58-64.

26. Water Measurement Manual,3rd ed., U.S. Department of the Interior, Bureau of Reclamation, 1997, pp.400.

27. Thomas J. Rhone and Daniel W. Bates, "Fish Protective Facilities at the Tracy pumping Plant-Central Valley Project California", 9th Hydraulics Division Conference, American Society of Civil Engineers, Seattle, WA, Aug 17-19, 1960.

28. Tracy B. Vermeyen and Perry L. Johnson, "Hydraulic performance of a flexible curtain used for selective withdrawal- a physical model and prototype comparison", Proceedings, ASCE National Hydraulic Engineering Conference, 1993.